TM 11-666

DEPARTMENT OF THE ARMY TECHNICAL MANUAL

ANTENNAS AND RADIO PROPAGATION

DEPARTMENT OF THE ARMY • FEBRUARY 1953

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The manuals on electronic fundamentals form a progressive series of educational texts which present the theory and application of electronics for the military services. The series starts with the basic electrical fundamentals and extends to the most recent technical concepts, as applied to telegraphy, telephony, radio, loran, facsimile, radio direction finding, radar, meteorological radio, television, and other military equipments. See SR 310–20–4 for published, available manuals in this series.

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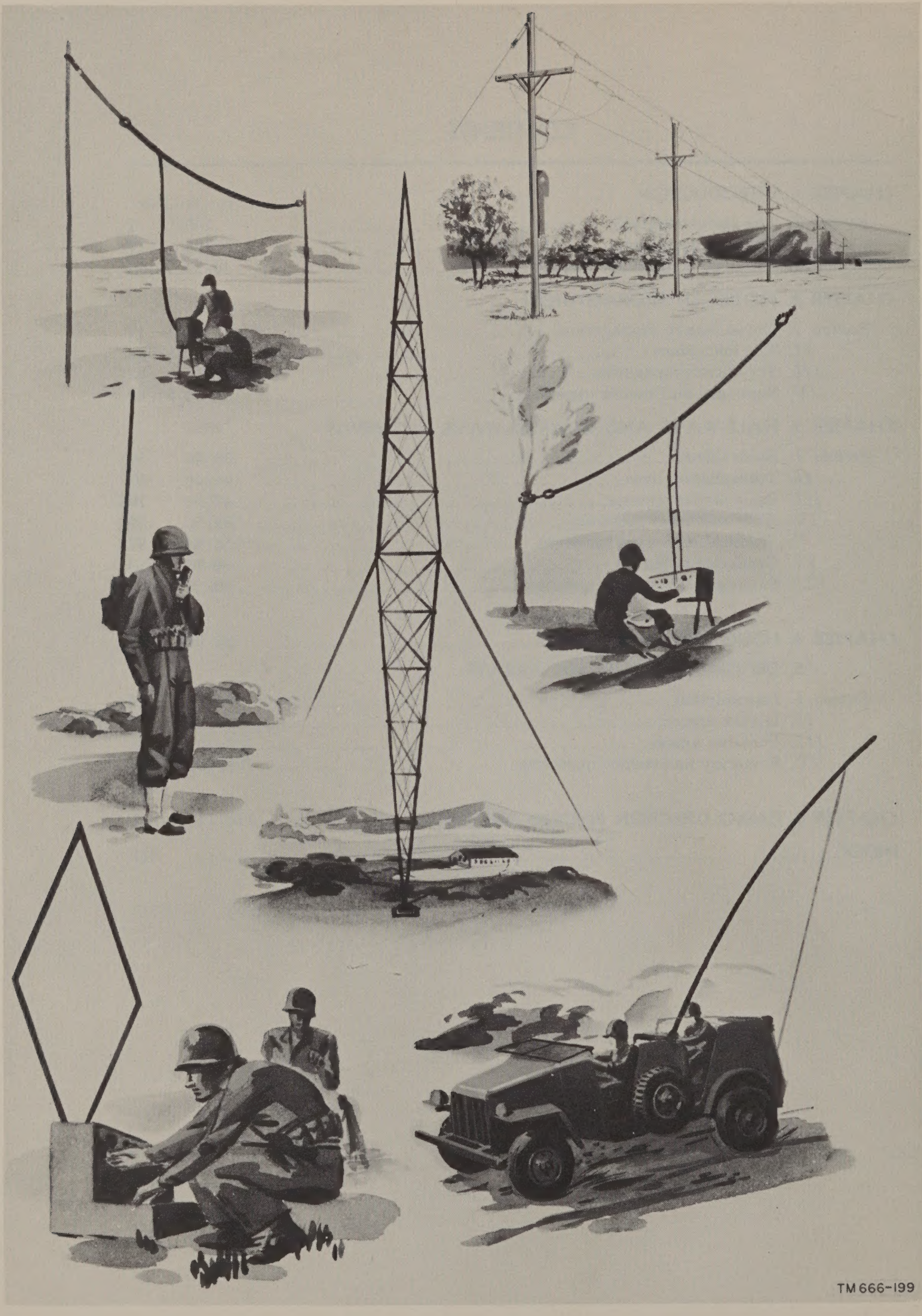


Figure 1. Assorted antennas and their uses.

CHAPTER 1
INTRODUCTION

Section I. THE ELECTROMAGNETIC WAVE

1. General

a. The study of antennas and wave propagation is essential to a complete understanding of radio communication, radar, loran, and other electronic systems. In such systems, energy in the form of radio or electromagnetic waves is generated by electronic equipment and fed to an antenna by means of special transmission lines. The antenna radiates this energy out into space at the speed of light (approximately 186,000 miles per second). Receiving antennas, when placed in the path of the traveling wave, absorb part of this energy and send it to the receiving equipment by means of a transmission line. Thus, the components required for successful transmission of intelligence by means of radio waves are a transmitter and transmission line, a transmitting antenna, a medium through which the waves travel (for example, the atmosphere surrounding the earth), a receiving antenna, another transmission line, and suitable receiving equipment. Figure 2 is a block diagram showing the arrangement of these components.

b. The ability to obtain successful communication by means of radio waves depends chiefly on the power of the transmitter, the distance between transmitter and receiver, and the sensitivity of the receiver. The ability of the earth's atmosphere to conduct the energy to its destination, together with the nature of the terrain between the sending and the receiving points, may, however, be responsible for the frequency selected; interfering signals may make reception impossible at a desired time, and the amount of noise present and transmission line losses may combine to make an otherwise good signal unintelligible. To understand the proper importance of all these factors it is necessary first to investigate the nature of the radio wave and the factors affecting its successful propagation.

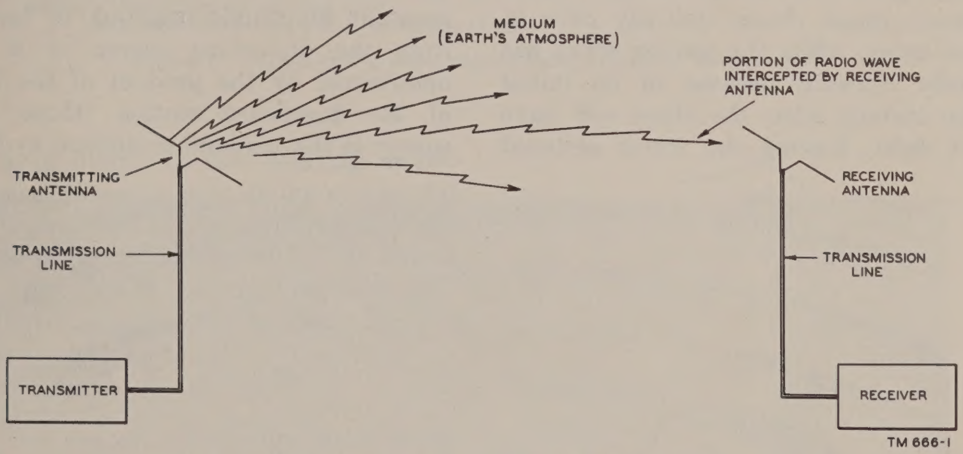


Figure 2. Simple radio communications network.

2. Wave Motion

a. Heinrich Hertz, in 1887, demonstrated that electromagnetic energy could be sent out into space in the form of radio waves. It is known, of course, that an induction field exists about any wire carrying an electric current. Another field, called the radiation field, exists, becomes detached from the wire, and travels through space to make radio communication possible. Attempts have

been made to illustrate the action involved by comparing it to the waves formed by dropping a stone on the smooth surface of a pond. Although the analogy is not exact, it does serve a useful purpose because it makes comparison with a well known physical action. Figure 3 shows such an event taking place, the waves appearing to be a series of regularly alternating crests and hollows moving radially outward in all directions from the point of disturbance on the surface of the water.

b. Figure 4 presents a graphical analysis of this action, showing how the stone imparts its energy to the water surface. A of figure 4 shows the falling stone just an instant before it strikes the water. Its energy has been derived from the gravitational pull exerted on it by the earth, and the amount of this energy depends not only on the weight of the stone but also on the height from which it has been dropped. B of figure 4 shows the action taking place at the instant the stone strikes the surface, pushing the water around it upward and outward, thereby imparting an initial velocity to the mass of water at this point of contact. In C of figure 4 the stone has sunk deeper into the water, which closes violently over it, causing some spray, while the leading wave has moved radially outward because of its initial velocity. An instant later, the stone will have sunk out of sight, leaving the water agitated (D of fig. 4). Here the leading wave has continued to move outward, and is followed by a series of waves of gradually diminishing amplitude; meanwhile, the agitation in the immediate vicinity of the original point of contact gradually subsides. Note that the leading wave has amplitude (note A, fig. 4) and wavelength (note B, fig. 4) corresponding to 1 complete cycle.

c. Of course, this action fails to compare with that of electromagnetic radiation, since a *continuous* wave motion is not imparted to the surface of the water by a dropped stone, the action just described being that of a damped oscillation. But suppose a string to be attached to the stone of figure 4 so that its upward and downward motion can be controlled from above. Before the event shown in *C* of figure 4, takes place, the stone is pulled sharply upward after its initial fall to the position shown in *A* of figure 5, and then lowered again to the position shown in *B* of figure 5. The result of these upward and downward motions is to reinforce the diminishing amplitude of the succeeding waves, and, if the timing and the downward force of the stone are exactly right, waves of constant amplitude continue to travel outward from the disturbing source at a velocity, v, determined by the product of the frequency, f, of the downward motion (those that impart energy to the medium) multiplied by the measured

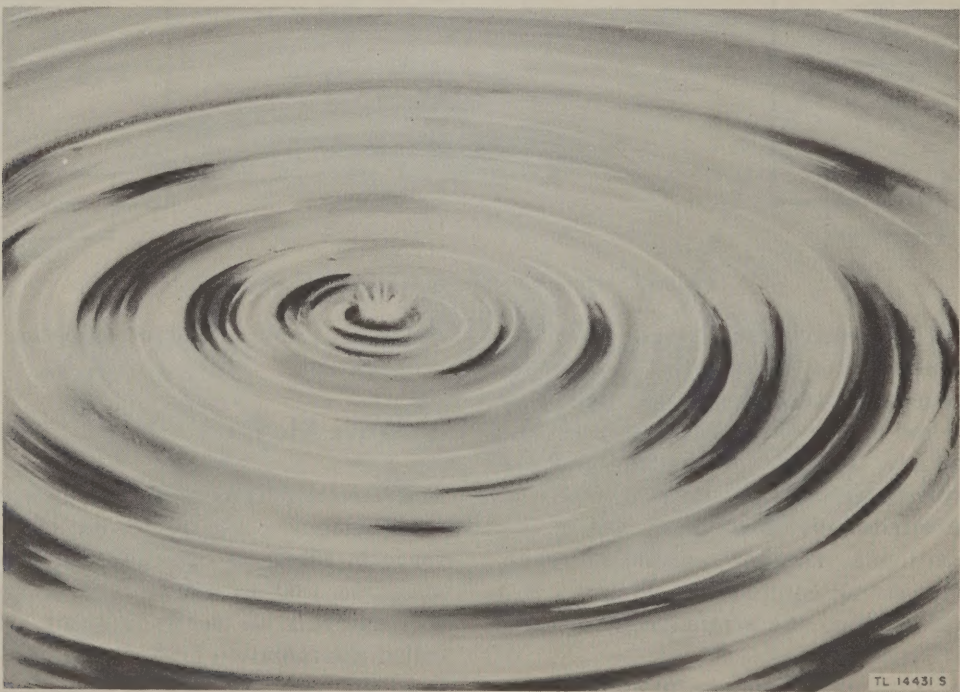


Figure 3. Formation of waves in water.

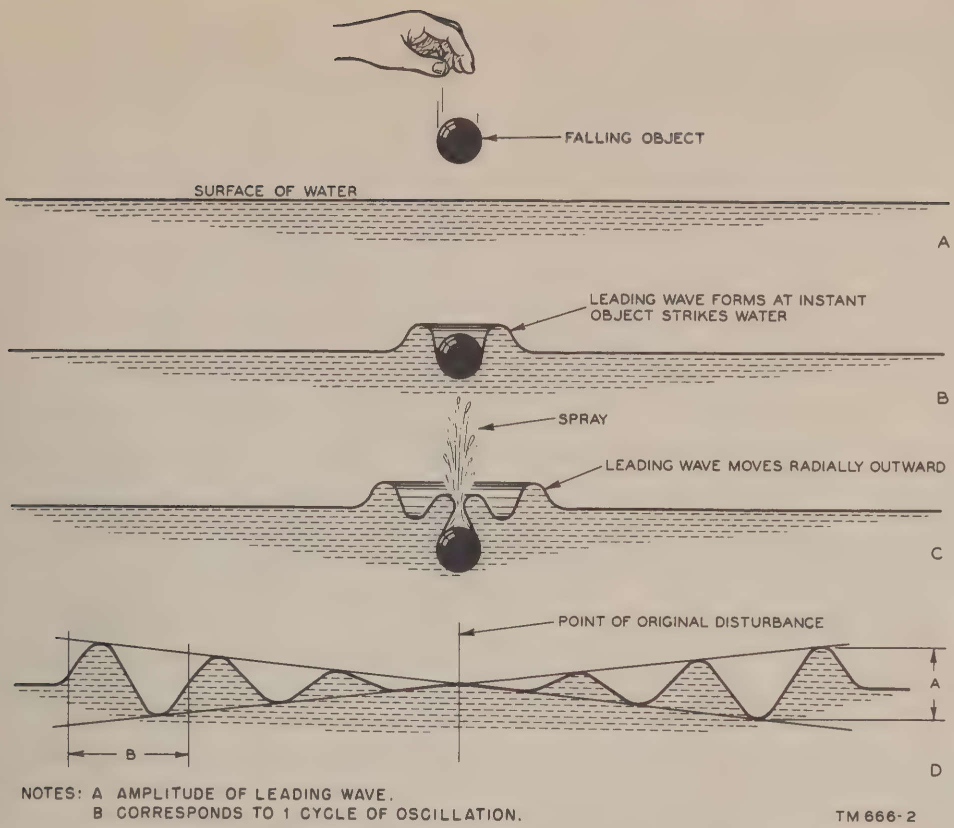


Figure 4. How a falling stone imparts wave motion to a water surface.

wavelength λ (lambda), of the resulting waves. (Since L is used conventionally as the symbol for inductance and l for dimensional length, the equivalent Greek letter, λ, is used for the length of waves.) Thus: $v=\lambda f$. If the frequency and the velocity of propagation are known, then the wavelength may be determined:

$$\lambda=v/f$$

d. This same type of action takes place at the antenna of a radio transmitter, the medium in this case being the free space about the antenna instead of a water surface, and the disturbing source a fluctuating induction field in place of a moving stone. The preceding formulas (*c* above) hold for this wave motion and for all types of wave motion, whether it be of water waves, sound waves in air, or light and electromagnetic waves in free space. It should be noted, however, that the term *free space* is used to denote the unobstructed medium through which radio waves travel. Free space implies that the source (transmitter and antenna in the case of radio waves) is surrounded by nothing except ordinary air or

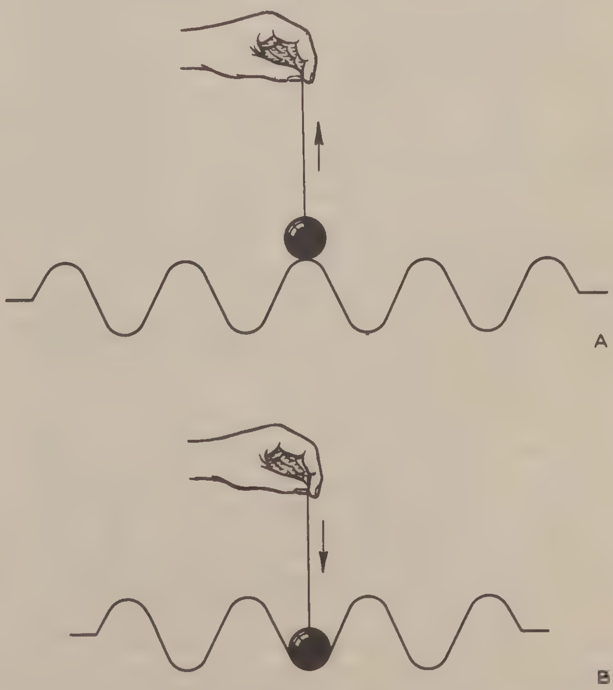


Figure 5. Formation of continuous waves in water.

vacuum. The presence of trees, hills, lakes, or other aspects of the local terrain modifies in each case the effective radiation of an electromagnetic wave. And thus, although the surface of the earth, or the air near its surface, is not considered to be free space, the formula in *c* above still will hold in terms of properly modified factors.

e. Like light and radiant heat, radio waves are a form of radiant energy propagated through space at a speed of nearly 300,000,000 meters (186,000 miles) per second. Thus, a wave alternating at a frequency of 1,000,000 cycles per second has a wavelength of approximately 982 feet.

Since: $\lambda = v/f = 186{,}000/1{,}000{,}000$
$\lambda = 0.186$ mile
Converting to feet: $\lambda = 0.186 \times 5{,}280$
$\lambda = 982$ feet.
Then one half-wavelength or $\lambda/2 = 982/2 = 491$ feet.

3. Radiation from a Half-wave Antenna

a. Although nothing has been said about the characteristics of a half-wave antenna, it is convenient to use this element in describing the mechanism of radiation. Simply stated, a half-wave antenna is one which is approximately a half-wave long at the operating frequency. For example, at 30 megacycles, a half-wave antenna is approximately 16 feet long. When power is delivered to such an antenna, two fields are set up by the fluctuating energy: one the *induction* field, which is associated with the stored energy (par. 6), and the other the *radiation* field, which moves out into space at nearly the speed of light. At the antenna, the intensities of these fields are large and are proportional to the amount of power delivered to the antenna. At a short distance from the antenna, and beyond, only the radiation field prevails. This radiation field is made up of an electric component and a magnetic component at right angles to each other *in space* and varying together in intensity.

b. Figure 6 shows the manner in which the radiation field is propagated away from the antenna. The electric and magnetic components are represented here by separate sets of flux lines, which are at right angles to each other and to the radial direction of propagation. The picture is representative of any plane containing the antenna, and applies for only a single instant of time. The magnetic flux lines are shown as circular lines having the axis of the antenna as their axis, so that they appear in the illustration as dots and crosses. The electric flux lines also are closed, or endless, lines in the present case, and consist essentially of arcs of circles lying in planes containing the antenna and joined in the manner shown. These electric flux lines reverse direction at precisely the places where the magnetic flux lines reverse, and their density varies along the radial direction in the way that the magnetic flux density varies. In fact, the electric flux density is everywhere proportional to the magnetic flux density.

c. The correct configuration of flux lines for a single instant of time is shown in figure 6. As time passes, these flux lines expand radially with the velocity of light, and new flux lines are created at the antenna to replace those that travel outward. Thus, oscillating electric and magnetic fields are produced along the path of travel. The frequency of the oscillating fields is the same as the frequency of the antenna current, and the magnitudes of both fields vary continuously with this current. The variations in the magnitude of the electric component (called the E field) and those of the magnetic component (called the H field) are in time phase, so that at every point in space the time-varying magnetic field induces a difference in voltage, which is the electric field. The electric field also varies with time, and its variation is equivalent to a current, even though it is not associated with a movement of charge. This is called the *displacement current,* and it establishes a magnetic field in precisely the way that a conduction current does. *Thus, the varying magnetic field produces a varying electric field, and the varying electric field, through its associated displacement current, sustains the varying magnetic field. Each field supports the other, and neither can be propagated by itself, without setting up the other.*

d. The mechanism by which the flux lines of the radiation field become separated from the antenna and are radiated out into space can be understood by considering the movement of the charges which pass back and forth along the length of the antenna as a result of the driving current. At an instant of time when positive charges are distributed along one half of the antenna, and negative charges along the other half, electric flux lines originate on the positive charges and terminate on the negative charges. These flux lines follow paths in space such as those indicated in *A* of figure 7. As time passes, the separated charges again come together, bringing the two ends of the

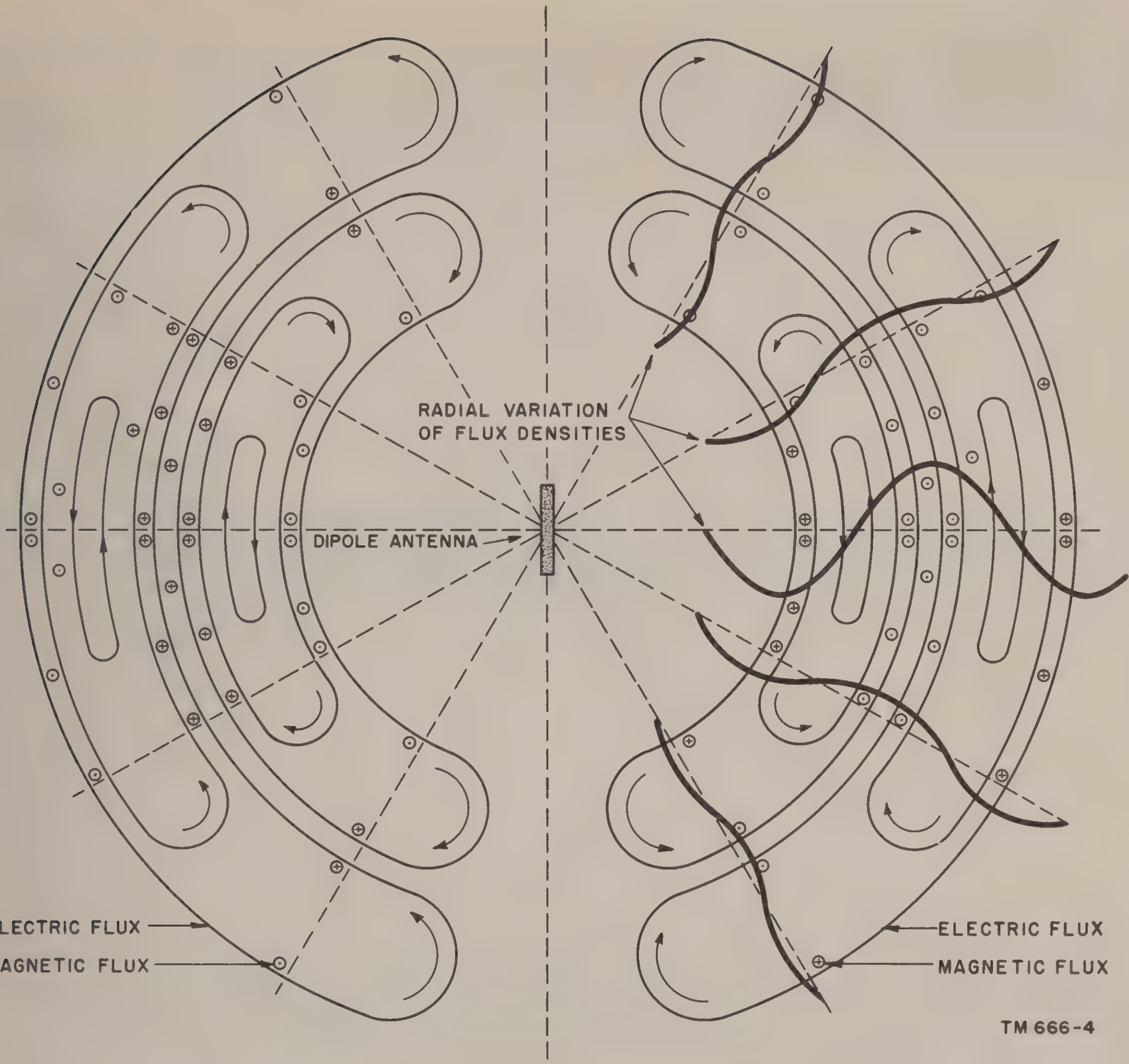


Figure 6. Electric and magnetic fields about an antenna.

flux lines together, as in *B* of figure 7. When the unlike charges meet, they seem to cancel each other, and the flux lines attached to them collapse and cease to exist. Thus, the two ends of the flux lines become joined, creating closed lines which are snapped free from the antenna and propagated outward, as shown in *C* and *D* of figure 7.

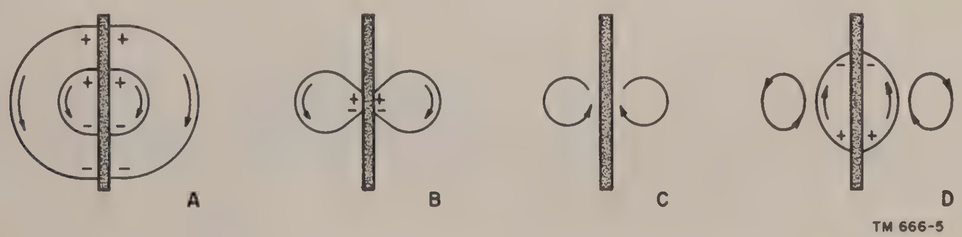


Figure 7. Creation of closed electric lines at an antenna.

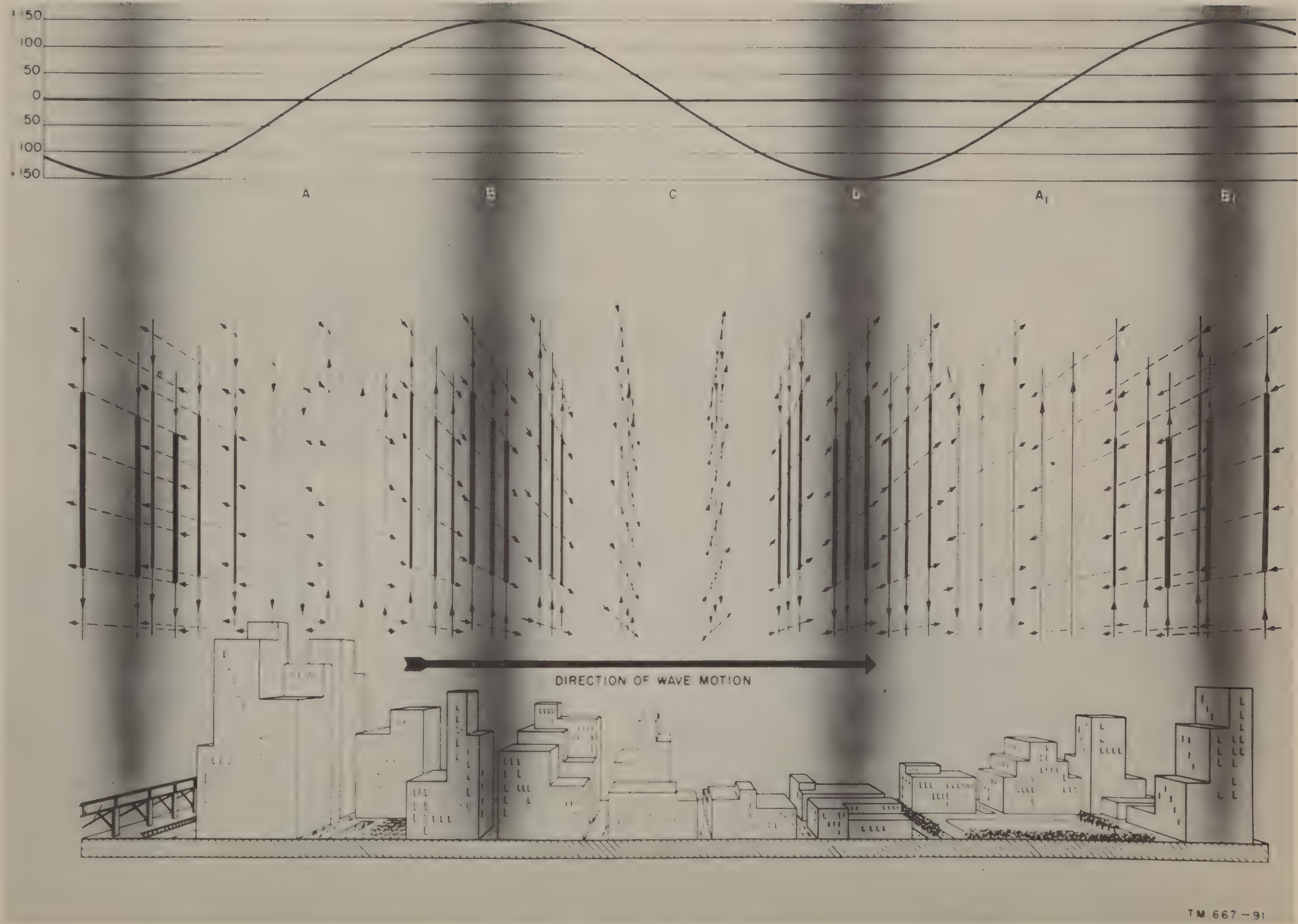


Figure 8. Plane transverse surface of wave front.

4. The Wave Front

Actually, the radiation field may be conceived of as a series of concentric expanding surfaces following one after the other. On each of these surfaces, the radiation field is at a constant phase of vibration and is called a wave front. Figure 3 illustrates this concept. If the surface of the water about the point of disturbance is examined, water waves are observed to be radiating outward, increasing in circumference as they travel. At a distance from the origin, the circular pattern becomes less apparent and, when a small transverse section of the disturbed surface is studied, only arcs of relatively large circles of the wave front appear, and these seem to be transverse straight lines. Similar effects occur with radio waves that are radiated from an antenna, so that, at great distances from the antenna, a small portion of the wave front may be taken to be a transverse plane surface (fig. 8). From the point of view of the observer, the wave fronts march past, varying sinusoidally in direction and magnitude, as shown by the graphs at the top of the picture.

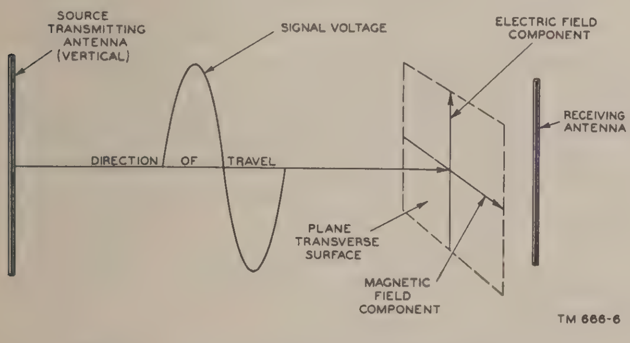


Figure 9. Components of electromagnetic wave.

a. E and H Fields. In considering the radio signal path between a transmitting and a receiving antenna, the concept of a moving wave front becomes important. This path is assumed to follow a straight line in the direction of travel. In traveling this way, the radio wave may be described as moving electromagnetic field, having velocity in the direction of travel, and with components of electric intensity and magnetic intensity arranged at right angles to each other (fig. 9). This figure indicates that the instantaneous amplitudes and phase relations of the electric field, *E*, and the magnetic field, *H*, change with time according to the frequency of the wave. In order to visualize this action, imagine a receiving antenna in the path of the oncoming wave (fig. 10). Now consider that the entire wave is moving at a constant speed in the direction indicated. The intensities of both the electric and the magnetic fields will be maximum at the same instant as the crest of the wave passes the antenna, and minimum at the same instant the zero point is reached, but at all times the fields are perpendicular to each other. It should be kept in mind that figure 10 shows only one transverse section of the entire wave front, which fills all the space shown in the figure.

b. Directional Conventions. The direction of the electric or magnetic component of an electromagnetic wave at any instant is determined by the conventions described below. It should be noted, however, that the electric and magnetic components of a *radiated* field are in phase in respect to time and 90° out of phase in respect to space, but that the electric and magnetic components of the *induction* field are 90° out of phase in respect to both time and space. Therefore, for the duration

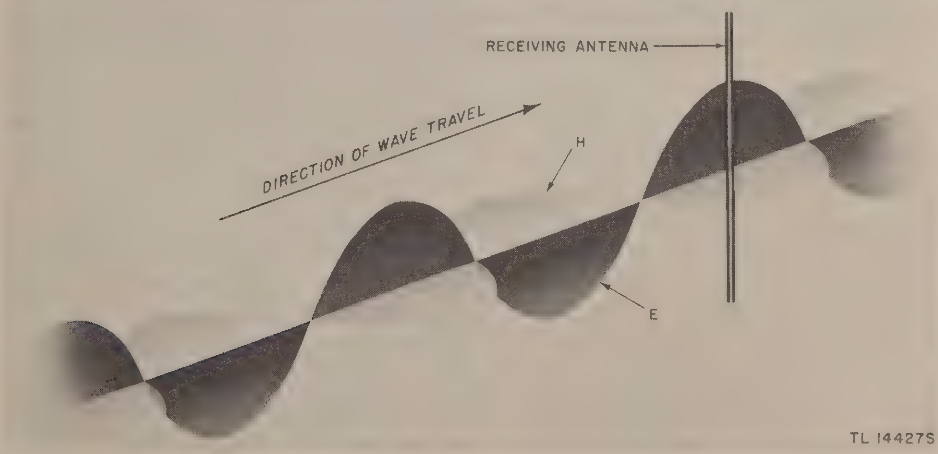


Figure 10. E and H fields of radiated wave.

of a given electric induction field, the magnetic induction field is first in one direction at right angles to the increasing electric field and then in the opposite direction for the decreasing electric field.

(1) *Electric field.* The direction of any electric field is, like that of voltage, taken to be from plus to minus; that is, an arrow representing the direction of an electric field carries the plus sign at its tail and the minus sign at its head. This convention is based on the arbitrary selection of a unit *positive* charge as a test charge, which in such a field would move from plus to minus.

(2) *Magnetic field* (*radiated*). If the radiated field is moving away from an observer with the arrows indicating direction of the electric field pointing downward, the direction of the magnetic field is given by arrows pointing to the left. This convention is based on the generation of a magnetic field by current defined as electron flow—that is, moving negative charges—and determined by use of the left-hand rule.

(3) *Magnetic field* (*induction*). To an observer looking outward from a transmitting antenna, an increasing electric field of downward direction would be accompanied by a magnetic field with arrows pointing to the left, and a decreasing electric field of downward direction would be accompanied by a magnetic field with arrows pointing to the right. By the same token, the electric induction field reverses direction for the duration of a given magnetic field.

5. Polarization

In describing the principal characteristics of a wave front, the *electric* field component is taken as the point of reference. For example, the intensity of a radio wave usually is measured in terms of the strength of the electric field, and the orientation of the wave in space usually is described in terms of the direction of wave travel and by the direction of the electric field. The direction of the electric field, in particular, determines the *polarization* of the wave. Thus, as shown in Ⓐ of figure 11, when the plane containing the electric field and the direction of travel is vertical, the wave is said to be polarized vertically; if the plane is horizontal, as in Ⓑ of figure 11 the wave is said to be polarized horizontally. This polarization of the wave front is an important factor in the efficient transmission and reception of signals. Thus, if a single-wire antenna is used to extract energy from a passing radio wave, maximum pickup will result when the antenna is so placed physically that it lies in the same direction as the electric field component. Therefore, a vertical antenna (one perpendicular to the ground) should be used for the efficient reception of vertically polarized waves (those transmitted from a vertical antenna), and a horizontal antenna should be used for the reception of horizontally polarized waves (those transmitted from a horizontal antenna). In both cases, the direction of travel is taken to be parallel to the earth's surface.

6. Field Intensity

a. The conventional measure of the field intensity of a radiated wave is, as mentioned in the previous paragraph, a measure of the intensity of the *electric* field. This intensity usually is expressed in volts, millivolts, or microvolts per meter, which is a measure of the dielectric stress produced by the electric field, or the voltage induced in a conductor 1 meter long when held so that it lies in the direction of the electric field and is at right angles to the direction of propagation and to the direction of the magnetic field. As the distance between the transmitting antenna and the receiving antenna becomes greater and greater, the field intensity of the radiated wave falls off proportionately to the distance. For example, if the received field intensity of a signal is 50 millivolts per meter at a distance of 25 miles, then at 50 miles, or twice the distance, the field intensity is one-half as much, or 25 millivolts. Thus, electric field intensity varies inversely with the distance from the transmitting antenna.

b. In order to understand this variation of the field intensity of a radiated wave, consideration must be given to the relationship between the *power* radiated and the field intensity. As was known before the era of electronics, the *power* of a radiated wave, such as a light wave, falls off as the *square* of the distance between the source of light and the point of measurement. Thus, if a lighted candle is placed in the center of a dark room, the intensity of its light will vary according to the square of the distance from it. In other

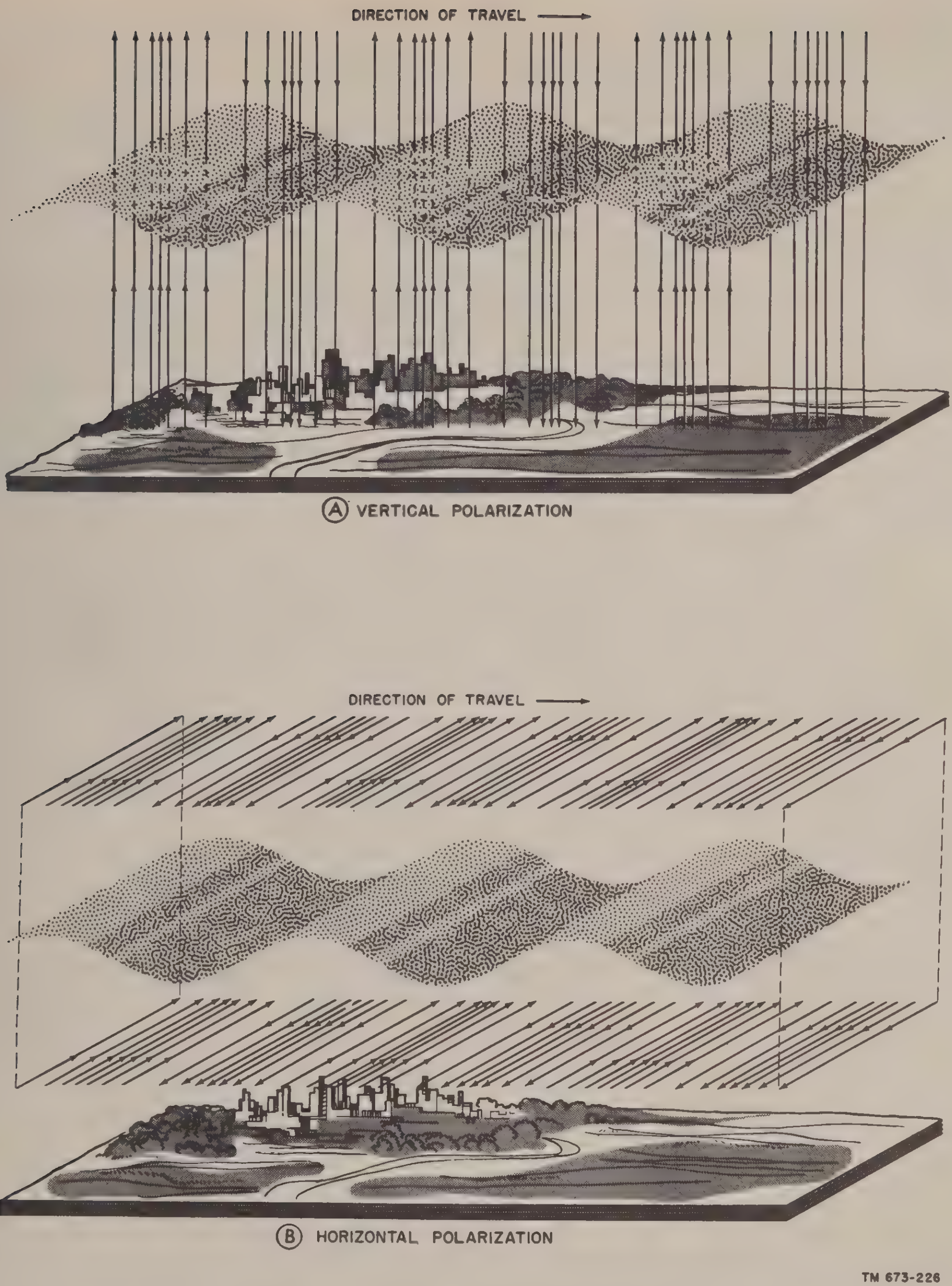


Figure 11. Vertical and horizontal polarization.

words, a sheet of paper held perpendicular to the rays of a candle and a certain distance from it will be lighted four times as brightly as one held at twice this same distance. The reason for this is illustrated in figure 12, where it may be seen that the same amount of light that is intercepted by the paper at A must be used to cover *four* times as great an area at B, which is *twice* as far from the candle as A. This law is expressed by the formula:

$$A=4\pi r^2$$

where A is the area of any portion of the surface of a sphere of radius, r, having its center at the source of the light. If r in figure 12 is equal to 1 foot, the area of the sheet at A is then $4\pi\ (1)^2$ or

4π, whereas the area of the sheet at B is equal to $4\pi\ (2)^2$ or 16π. The amount of light intercepted at A is equivalent to the amount intercepted at B, which has an area four times as great. This same law holds for the field intensity of electromagnetic waves when the *power* intercepted in a unit area is considered. However, since electric power expressed in terms of the voltage present is proportional to E^2 (because $P=E^2/R$), then the square of the voltage falls off as the square of the distance, or voltage itself falls off as the distance.

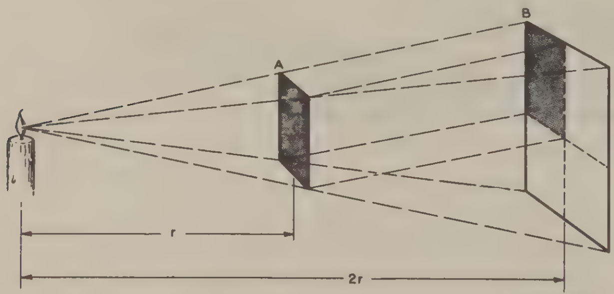


Figure 12. How light waves decrease in intensity as the square of the distance.

c. This analysis of field strength and the manner in which it decreases at a distance from the radiating antenna supplies the basis for understanding the relationship between the various fields and their components present at a transmitting antenna. As mentioned in paragraph 3*a*, *two* major fields are set up about a transmitting antenna when alternating current power is applied. The radiation field persists to great distances, and the manner in which the power and intensity of this field are related to distance has been described above. The induction field, on the other hand, is present only in the immediate area of the transmitting antenna, since its power falls off as the fourth power of the distance. Close by the antenna, the induction field is stronger than the radiation field, but, at a distance equal to a few wavelengths of the frequency transmitted, the induction field is so small as to be negligible. The induction field is the field usually associated with the voltage and current in any conductor, and as such not only is the electric component at right angles to the magnetic component (as it is about any inductance carrying alternating current), but also the usual phase shift of 90° between voltage and current prevails. The result is that the induction field is made up of two fields separated in space by 90° and in time by 90°, or (as sometimes expressed) two fields in *space quadrature* and in *time quadrature.* The electric and magnetic components of the radiation field, as has been shown, are also in space quadrature but are in time phase.

d. Perhaps some notion of the characteristics of the induction field may be gained from considering that its components are the stored energy usually associated with a resonant circuit—the energy stored alternately by an inductor and a capacitor. Thus, the energy in the electrostatic field is the energy in the magnetic field (oscillating continuously from one to the other), and this energy in either case is returned to the antenna circuit. Therefore, the power in the radiation field is the power delivered to a transmitting antenna, less the heat loss in the antenna itself.

Section II. WAVE PROPAGATION

7. The Atmosphere

The study of wave propagation is concerned chiefly with the properties and effects of the actual medium through which radio waves must travel in following any given path between a transmitting antenna and a receiving antenna. Since the atmosphere about the earth is not uniform, changing with a change in height or geographical location, or even with a change of time (day, night, season, year), the lack of uniformity appreciably influences the passage of electromagnetic waves through it, thereby adding many new factors to complicate what at first might seem to be a relatively simple communication problem. A knowledge of the composition of the earth's atmosphere is extremely important in solving this problem, and therefore, for purposes of understanding wave propagation, various layers of the atmosphere have been distinguished. These are the *troposphere*, the *stratosphere*, and the *ionosphere*. Their relative positions are shown in figure 13.

a. The Troposphere. The troposphere is that portion of the earth's atmosphere extending from the surface of the earth to heights of about 11 km (kilometers), or approximately 6½ miles. The temperature in this region varies appreciably with altitude.

b. The Stratosphere. The stratosphere is that portion of the earth's atmosphere lying between

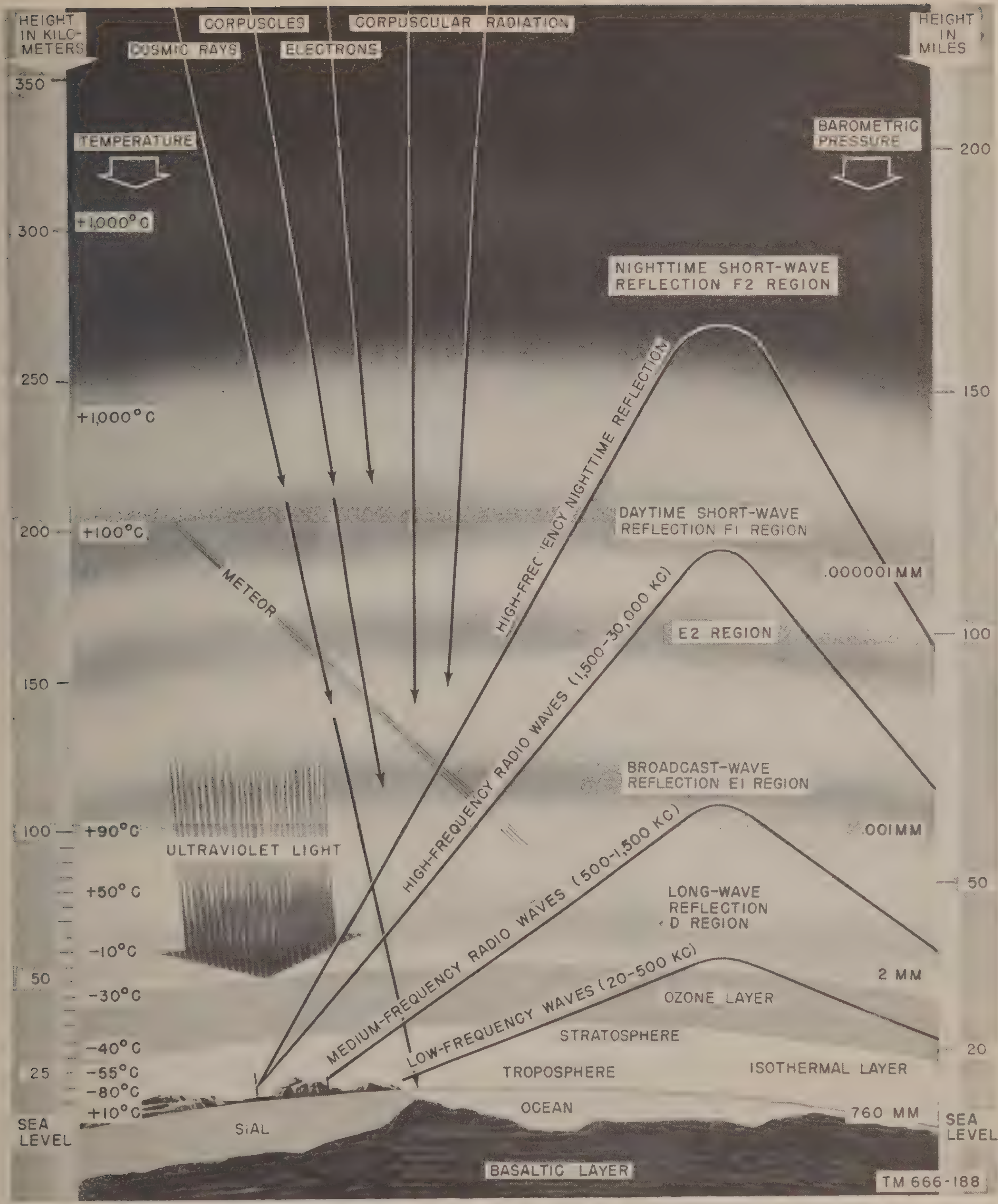


Figure 13. Layers of the earth's atmosphere.

the troposphere and the ionosphere. The temperature in this region is considered to be almost constant, and, hence, it is called the isothermal region.

c. The Ionosphere. Besides the usual variations of moisture content and temperature, and the variations in density associated with a change in elevation, the atmosphere is distinguished principally by the variation in amount of ionization present. The ionosphere accordingly is defined as that portion of the earth's atmosphere above the lowest level at which ionization affects the transmission of radio waves. The ionization of this layer is large compared with that near the surface of the earth. It extends from about 50 kilometers to 250 kilometers above the earth. The ionosphere is itself composed of several layers, as shown in figure 13, where ionization occurs at different levels and intensities. The properties of these layers and their effects upon the propagation of electromagnetic waves are treated in detail in the next chapter.

8. Frequency Classifications

An understanding of the effects of the atmospheric layers described above is complicated further by variations in the frequency of the transmitted wave. The characteristics of low-frequency propagation are different from those of high-frequency propagation, and therefore, for ease of identification, the frequencies of propagation usually are classed in ranges, as shown in table I. The choice of a given frequency as the point of division between classes, such as that between the very-high frequencies and the ultrahigh frequencies, is more or less arbitrary and is agreed upon for convenience. *Note that in this manual only those radio frequencies below 30 mc (megacycles) per second are considered.* The special considerations involved in the use of higher frequencies may be found in TM 11–667, Higher-frequency Techniques, and in TM 11–673, Generation and Transmission of Microwave Energy.

Table I. Radio-Frequency Classifications

Frequency (mc)	Description	Abbreviation
Below .03	Very-low frequency	vlf
.03 to .3	Low frequency	lf
.3 to 3.0	Medium frequency	mf
3.0 to 30	High frequency	hf
30 to 300	Very-high frequency	vhf
300 to 3,000	Ultrahigh frequency	uhf
3,000 to 30,000	Superhigh frequency	shf
30,000 to 300,000	Extremely-high frequency.	ehf

9. Propagation in the Atmosphere

There are two principal ways in which radio waves travel from a transmitter to a receiver: by means of ground waves which travel directly from the transmitter to the receiver, and by means of sky waves which travel up to the electrically conducting layers of the earth's atmosphere (the ionosphere), and are reflected by them back to the earth. Long-distance radio transmission takes place principally by means of sky waves, and short-distance transmission and all ultrahigh-frequency transmission take place by means of ground waves. Some forms of transmission consist of combinations of both. The propagation of the ground wave is in part affected by the electrical characteristics of the earth (soil or sea), and by *diffraction*, or bending, of the wave with the curvature of the earth. These characteristics differ in different localities, but under most conditions they are practically constant with time. Sky-wave propagation, on the other hand, is variable, since the state of the ionosphere is always changing and this, therefore, affects the reflection, or the refraction, of the waves.

a. Reflection.

(1) The reflection of a radio wave is like that of any other type of wave. For instance, when a beam of light falls on the surface of a mirror, nearly all of it is turned back or reflected. As with light waves, the efficiency with which reflection of radio waves occurs depends on the material of the reflecting medium. Large, smooth, metal surfaces of good electrical conductivity (such as copper) are very efficient reflectors of radio waves, reflecting nearly all of the energy carried by the incident waves. The surface of the earth is itself a fairly good reflector of radio waves, particularly for waves that are incident at small angles from the horizontal; and the ionosphere, even though it is not a surface such as a mirror, is also a fairly good reflector of radio waves.

(2) Figure 14 shows a planar wave front reflected from a smooth surface. It should

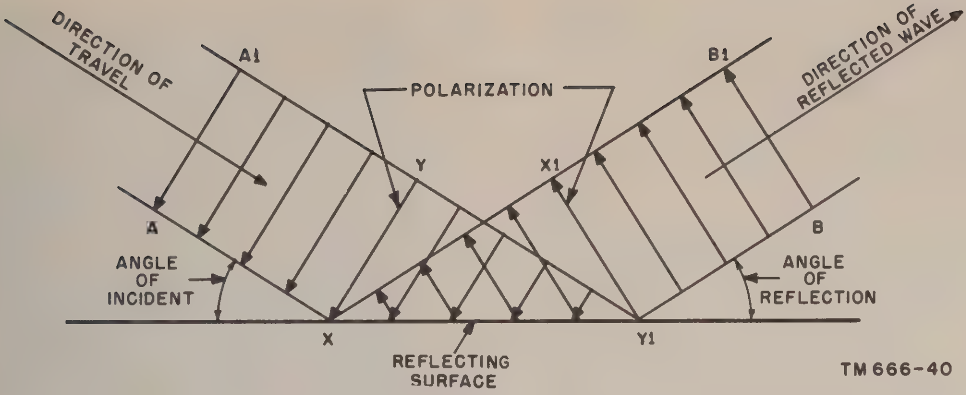


Figure 14. Reflection of a planar wave front.

be remembered here that, as in the reflection of light, the angle of incidence is always equal to the angle of reflection. However, the incident wave front, A–$A1$, is reversed by the reflecting surface and appears at B–$B1$ 180° out of phase. The reason for this is that point X of the incident wave reaches the reflecting surface before point Y and is reflected to point $X1$ during the time it takes for point Y on the wave front to move to the point of reflection $Y1$. The parallel arrows indicate this change in phase.

b. Refraction.

(1) If a beam of light shines on a smooth surface of water, some of the light will be reflected and the remaining portion will penetrate the water, as shown in figure 15. The phenomenon by which light waves penetrate the water in the manner shown is called *refraction*, and can be observed readily by examining a glass of water into which a spoon is immersed. If viewed from an angle, the spoon appears broken or bent at the point where it enters the surface of the water. The reason for this is that light waves travel at a slower speed through water than through air. Thus, in figure 15, the direction of travel of the refracted light is different from that of the light beam incident on the surface of the water. Figure 16 shows how this change of direction of the light beam occurs. The parallel lines in this figure, which look like steps of a ladder, represent wave fronts of a beam of light incident on the surface of the water. It will be recalled that a wave front is a surface of equal phase perpendicular to the direction of travel of the wave. In the case of water waves previously discussed, the crests of adjacent circular expanding ripples would correspond to the wave fronts shown in the figure.

(2) Consider the wave front, A–$A1$ (fig. 16), one portion of which is arriving at the surface of the water. Since the speed of light is less in water than it is in air, the point marked A will advance the distance, d_1, in a given length of time, whereas the point marked $A1$ will travel a greater distance, d_2, in the same length of time, since it is still passing through a faster medium. As a result, the wave front will be turned into a new direction, and the beam will follow this new direction. Note that refraction occurs only when the wave or beam of light approaches the new medium in an oblique direction; if the whole wave front arrives at the new medium at the same moment, it is slowed

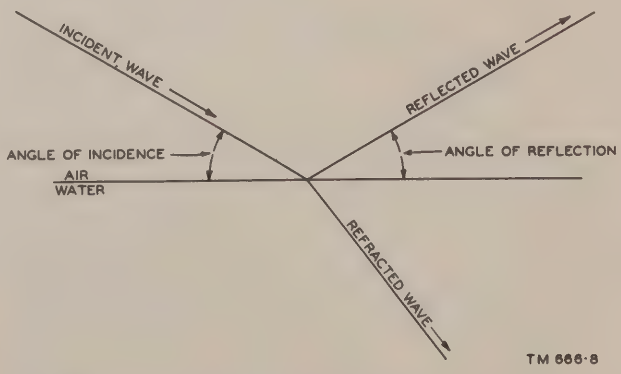


Figure 15. Reflection and refraction of a light beam.

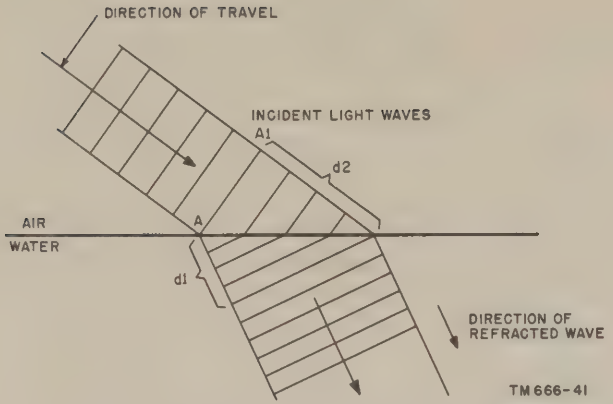


Figure 16. Bending of a wave front by refraction.

up uniformly and no bending occurs. The amount any wave is refracted or bent as it passes from one medium to another is called the *refractive index.* This index depends on the relative densities of the two media and is actually a ratio which compares the velocity of an electromagnetic wave through a perfect vacuum to its velocity through a denser medium such as the earth's atmosphere.

c. Diffraction. If a beam of light in an otherwise blacked-out room shines on the edge of an opaque screen, it will be observed that the screen will not cast a perfectly outlined shadow. The edges of the shadow are not outlined sharply because the light rays are bent around the edge of the object and decrease the area of total shadow. The diffraction or bending of a light wave around the edge of a solid object is slight. The lower the frequency of the wave, or the longer the wavelength, the greater the bending of the wave. Thus, radio waves are more readily diffracted than light waves, and sound waves more than radio

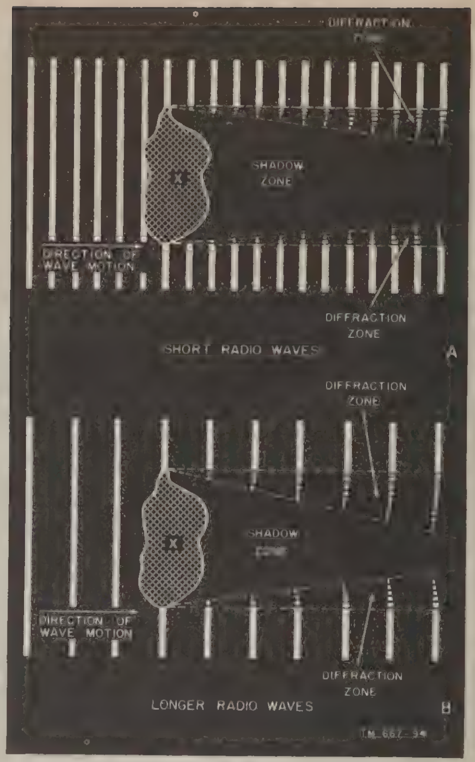


Figure 17. Diffraction of waves around solid object.

waves. *A* and *B* of figure 17 illustrate this phenomenon and help to explain why radio waves of the proper frequency can be received on the far side of a hill or other natural obstruction, and why sound waves can be heard readily from around the corner of a large building. Diffraction is an important consideration in the propagation of radio waves at a distance, because the largest object to be contended with is the bulge of the earth itself, which prevents a *direct* passage of the wave from the transmitter to the receiver. This problem is analyzed in detail in paragraphs 12 to 18 on ground-wave propagation.

Section III. SUMMARY AND REVIEW QUESTIONS

10. Summary

a. Electromagnetic waves are a form of radiant energy propagated into space at nearly the speed of light, 300,000,000 meters or 186,000 miles per second.

b. A radio wave may be described as a moving electromagnetic field having velocity in the direction of travel.

c. The wavelength of a radio wave in free space is equal to its velocity divided by its frequency ($\lambda = v/f$).

d. When power is delivered to an antenna, two fields are set up proportional to this power, an induction field and a radiation field.

e. At a distance from the antenna, only the radiation field prevails.

f. The radiated field has both electric and magnetic field components. Each field component supports the other, and neither can be propagated by itself without setting up the other.

g. The wave front of an electromagnetic wave is an expanding spherical surface all the points of which are of the same phase.

h. The electric and magnetic field components of a wave front are at right angles to each other and to the direction of travel.

i. The direction of the components of a radiated field are determined by convention: If the field is moving away from an observer with the direction of the electric field given as downward, the direction of the magnetic field is to the left.

j. The polarization of an electromagnetic field is determined by the direction of its electric component.

k. When the direction of the electric field is vertical, the wave is said to be polarized vertically; when the electric field is horizontal, the wave is said to be polarized horizontally.

l. Vertical antennas should be used for the transmission and reception of vertically polarized waves, and horizontal antennas for horizontally polarized waves.

m. The power in a radiated field at any point is measured in terms of the intensity of its electric field, which is expressed as volts, millivolts, or microvolts per meter. This intensity is a measure of the dielectric stress produced by the electric field, or the voltage induced in a conductor 1 meter long so held that it lies in the direction of the electric field and is at right angles to the direction of the magnetic field and to the direction of propagation.

n. The power of any radiated wave falls off as the square of the distance between the source and the point of measurement.

o. The intensity of the electric field of radiated electromagnetic waves falls off proportionally as the distance.

p. At a distance of approximately 10 wavelengths, or less, of the frequency transmitted, the power in the induction field is so small as to be negligible.

q. The induction field is made up of two fields (the electrostatic and the magnetic) separated in space by 90° and in time by 90°—that is, in space quadrature and in time quadrature.

r. The electric and magnetic components of the radiation field are in space quadrature and in time phase.

s. The energy in the induction field is the stored energy usually associated with a resonant circuit, being returned each cycle to the antenna circuit, except for slight losses.

t. The power in the radiation field is the power delivered to the antenna less the heat losses in the antenna circuit itself.

u. The atmosphere is composed of three regions, named in order of their relative heights—the troposphere, the stratosphere, and the ionosphere.

v. The ionosphere is defined as that portion of the earth's atmosphere above the lowest level at which ionization affects the transmission of radio waves. It is composed of several layers in which ionization occurs at different levels and intensities.

w. The propagation of radio waves depends on the frequency of the wave, the location and height of the antenna, and the ability of the earth's atmosphere to conduct the wave.

x. Long-distance transmission takes place principally by means of sky waves, and short-distance transmission and all ultrahigh-frequency transmission take place by means of ground waves.

y. Sky-wave propagation is variable, depending on the reflection or refraction of the wave from the ionosphere; ground-wave propagation is more constant, depending on the characteristics of the terrain, on reflection from the earth's surface, and on the diffraction of the wave around the curvature of the earth.

z. Radio waves reflected from the surface of the earth, from large metal objects, and from the ionosphere suffer a change of phase polarization of the wave front.

aa. Refraction is the bending of the beam of a radio wave when it passes from a medium of one density to that of another.

ab. The refractive index is a ratio that compares the velocity of an electromagnetic wave through a perfect vacuum to its velocity through a denser medium.

ac. Diffraction is the bending of a wave around the edges of a solid object; the lower the frequency, or the longer the wavelength, the greater is the bending of the wave.

11. Review Questions

a. Describe an electromagnetic wave.

b. What is the velocity of propagation of a radiated wave in free space?

c. Describe simple wave motion in water.

d. Give the formula for the length of any wave in terms of its velocity and frequency.

e. When did Hertz first demonstrate the radiation of an electromagnetic wave?

f. What two fields are set up about a transmitting antenna?

g. Describe the components of the radiated field.

h. What is the conventional determination of the direction of the components of the radiated field?

i. What is a vertically polarized wave? A horizontally polarized wave?

j. What type of antenna should be used for receiving vertically polarized waves?

k. What is the unit used in measuring the intensity of a radiated field?

l. What is the meaning of the expression *microvolts per meter?*

m. Give a possible explanation of the propagation of radio waves away from an antenna.

n. What is the relationship between power and distance for a radiated wave?

o. How are the components of the induction field related in time and space? The components of the radiated field?

p. How do the power and the intensity of the electrostatic field vary with distance? Of the magnetic field? Of the radiated field?

q. Describe the storage action of the induction field.

r. How is the power in the radiation field related to the total power delivered to the antenna?

s. Name the major regions of the atmosphere and describe the characteristics of each.

t. Define the ionosphere.

u. What major factors affect the propagation of radio waves?

v. What type of transmission uses sky waves? Ground waves?

w. What effect does reflection have on the phase of a wave front?

x. What is refraction?

y. Define the refractive index.

z. What is diffraction? How does it vary with frequency?

CHAPTER 2

MODES OF PROPAGATION

Section I. GROUND-WAVE PROPAGATION

12. Types of Ground Waves

a. Ground-wave propagation refers to those types of radio transmission that do not make use of reflections from the ionosphere. Therefore, the field intensity of ground waves depends on other factors—the transmitter power, the characteristics of the transmitting antenna, the frequency of the waves, the diffraction of the waves around the curvature of the earth, the electrical characteristics (conductivity and dielectric constant) of the local terrain, the nature of the transmission path, and also, local meteorological conditions such as the distribution of the water vapor content of the atmosphere. Most of the received ground-wave field intensity can be accounted for in terms of certain of these factors. Moreover, the earth itself is a semiconductor, and, upon contact with its surface, some of the energy of the radiated wave is absorbed and rapidly dissipated in the form of heat. Thus, the losses suffered by ground-wave transmission are sometimes excessive and its use generally is limited to moderate-distance communication (up to several hundred miles) at low frequencies and to exceptional high-frequency applications.

b. Figure 18 shows the way in which ground waves take a direct or reflected course from the transmitter to the receiver, or may be conducted by the surface of the earth and also refracted in

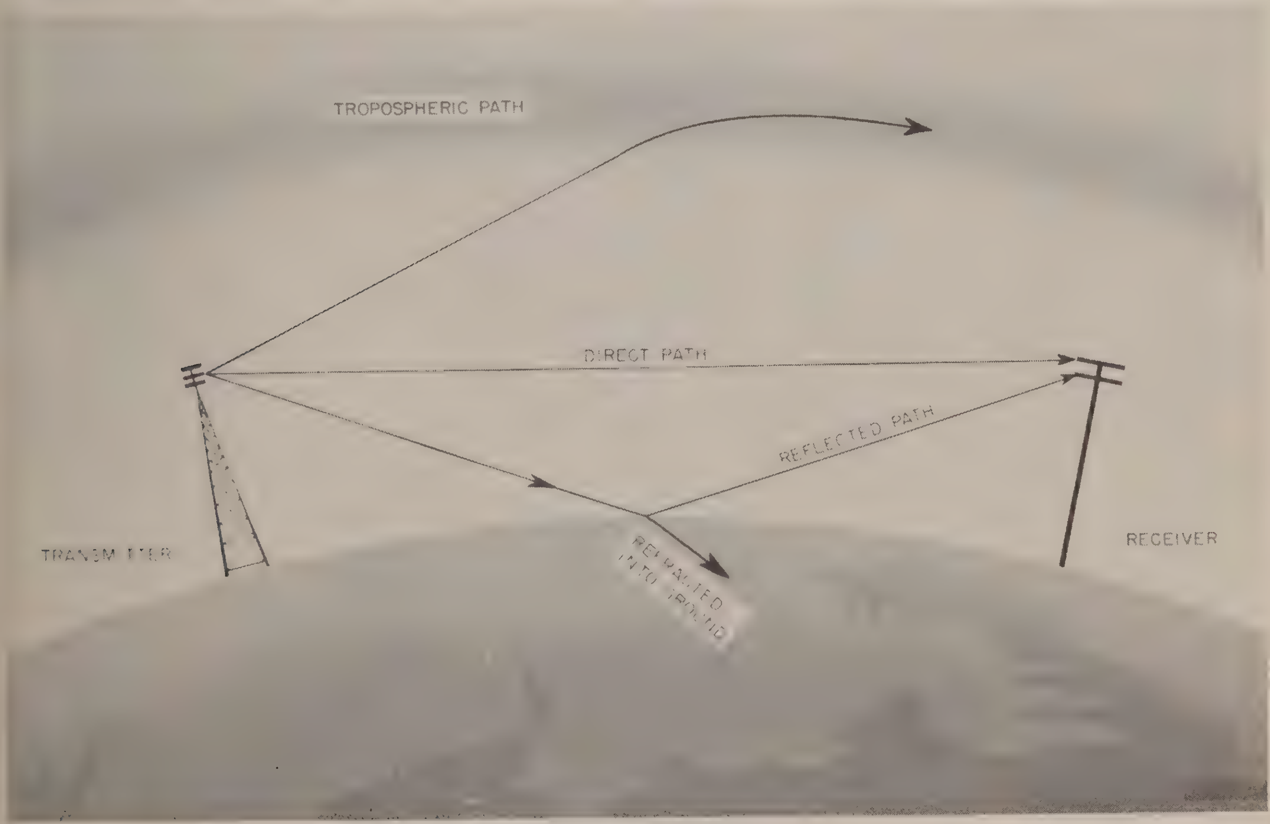


Figure 18. Possible routes for ground waves.

the troposphere. The resulting ground wave, therefore, can be considered as being composed of one or more of the following components: the *direct wave*, the *ground-reflected wave*, the *surface wave*, and the *tropospheric wave*.

13. Direct-Wave Component

a. The direct wave is that component of the entire wave front wnich travels directly from the transmitting antenna to the receiving antenna.

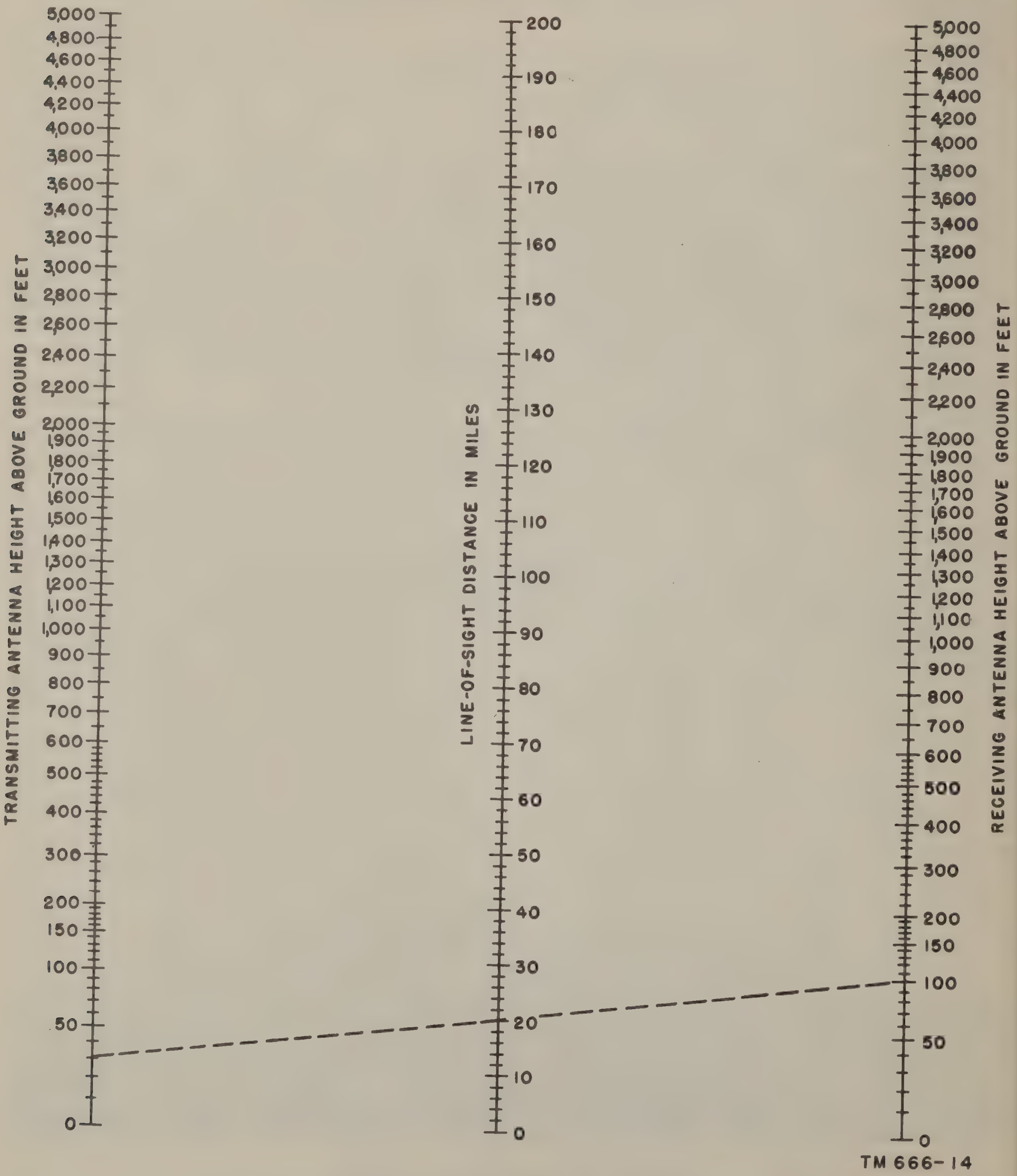


Figure 19. Nomograph—antenna heights and line-of-sight distance.

This component of the ground wave is limited only by the distance to the horizon, or line of sight, from the transmitter plus the small distance added by the atmosphere diffraction of the wave around the curvature of the earth. The total limiting distance, then, is computed easily by assuming an earth with a radius 4/3 times its proper radius. Such an earth would have a larger circumference and, hence, a longer distance to the horizon. This distance can be extended by in-

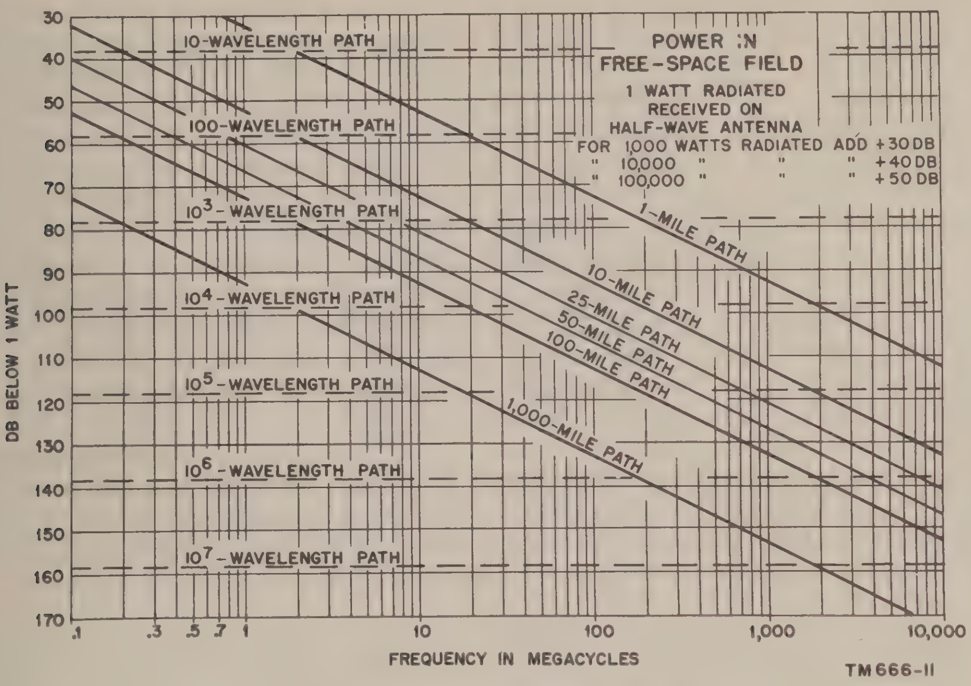


Figure 20. Attenuation of power with frequency and distance.

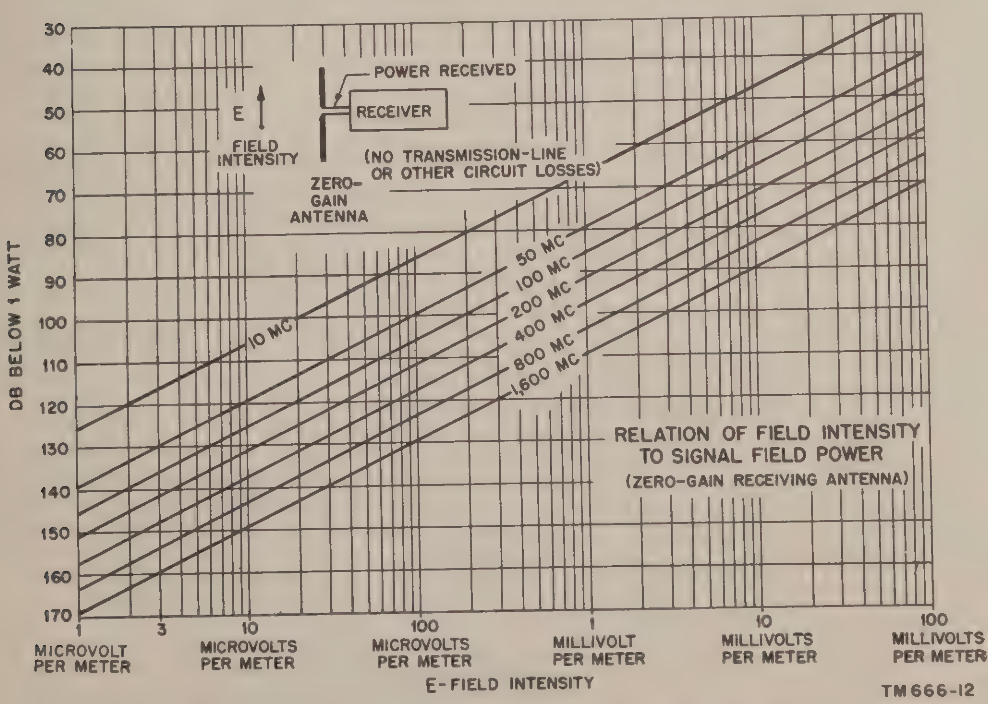


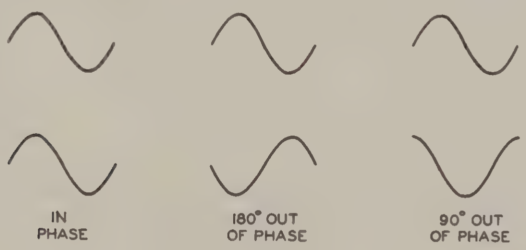
Figure 21. Attenuation of power in terms of field intensity.

creasing the height of either the transmitting or the receiving antenna, and so effectively extending the horizon. The nomograph of figure 19 gives an approximation of the line-of-sight transmission range without any mathematical calculations. Simply lay a straightedge on the chart so that it is alined with both the receiving-antenna height scale and the transmitting-antenna height scale, which are arranged on the two outside vertical lines of the chart. The transmission range then is indicated on the center vertical line at the point where the straightedge crosses it. An instance is shown by the dotted line—If the transmitting-antenna height is 30 feet and the receiving-antenna height is 100 feet, the line-of-sight transmission range is approximately 20 miles.

b. The electric field intensity of a direct wave varies inversely with the distance of transmission, as described in paragraph 6. This inverse-distance attenuation is shown by the graph in figure 20. For instance, the chart shows that for a 10-megacycle wave, 1 watt of radiated power suffers an attenuation of more than 80 db (decibels) below 1 watt over a 25-mile direct-wave path. This may be converted into terms of electric field intensity (microvolts per meter) by referring to figure 21. On this latter chart, note that at 10 megacycles a loss of 80 db below 1 watt results in an electric field intensity of about 200 microvolts per meter. Also, note that the attenuation increases as the frequency of transmission is increased, but that attenuation is constant when distance is read in terms of wavelength, since the higher the frequency, the shorter the distance represented by a given number of wavelengths. Furthermore, the direct wave is not affected by the ground or by the earth's surface, but is subject to refraction in the tropospheric air between the transmitter and the receiver. This refraction is particularly important at very high frequencies and is explained in greater detail in paragraphs 17 and 18.

14. Ground-Reflected Component

a. The ground-reflected component, as its name indicates, is the portion of the radiated wave that reaches the receiving antenna after being reflected from the ground or from the sea. For communi-



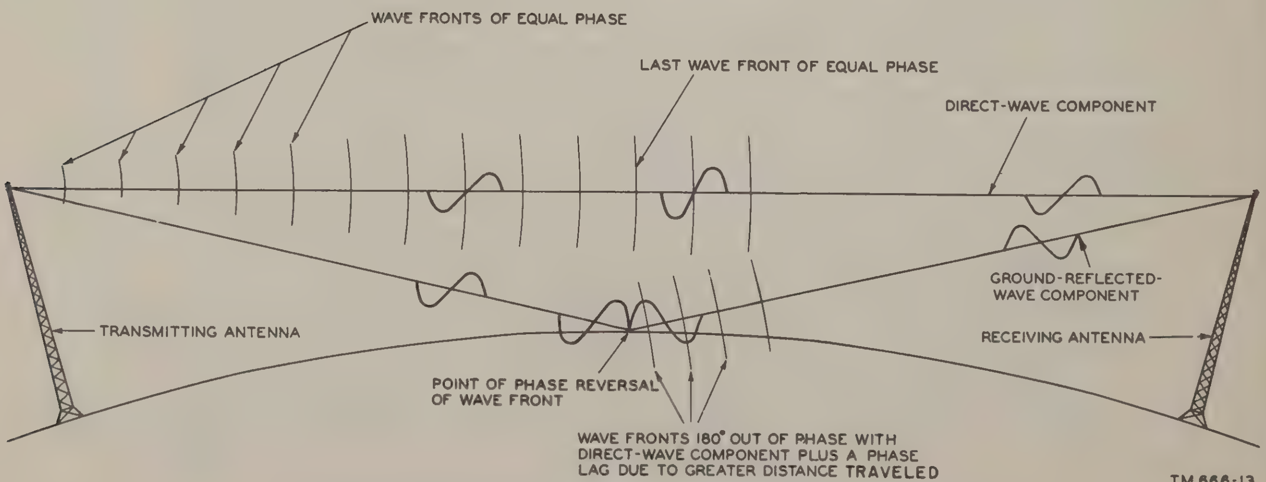


Figure 22. Comparison of wave fronts of direct and reflected waves.

cation between points lower than a few thousand feet and separated by a distance of several miles, the ground-reflected wave takes on an importance comparable to the direct wave as a means of propagation. Upon reflection from the earth's surface, the reflected wave undergoes a phase reversal of 180°, as noted previously, and this fact is important in determining the effect of its combining with the direct-wave component upon arrival at the point of reception. Since the reflected component travels a longer time in reaching its destination, a phase displacement over and above the 180° shift caused by reflection will result.

b. In figure 22, it may be seen that the waves start out with fronts of equal phase and continue in phase up to the point of reflection of the ground component. Beyond this point, corresponding wave fronts are 180° out of phase, plus whatever small phase displacement results from the relatively longer path of the reflected component. Where the reflected component strikes the ground at a small angle of incidence, the time lag will be small. The reflected wave will arrive at the receiving antenna nearly 180° out of phase with the direct wave, and a cancelation of signal energy will result. This cancelation effect can be minimized by increasing the height of either antenna, since this tends to decrease the phase difference between the direct and the reflected components, and thus decreases the degree of signal voltage cancelation.

15. Surface-Wave Component

a. The surface wave is that component of the ground wave that is affected primarily by the conductivity and dielectric constant of the earth and is able to follow the curvature of the earth. When both transmitting and receiving antennas are on, or close to, the ground, the direct and ground-reflected components of the wave tend to cancel out, and the resulting field intensity is principally that of the surface wave. The surface-wave component is not confined to the earth's surface, however, but extends up to considerable heights, diminishing in field strength with increased height. Because part of its energy is absorbed by the ground, the electric intensity of the surface wave is attenuated at a much greater rate than inversely as the distance. This attenuation depends on the relative conductivity of the surface over which the wave travels. Table II shows the relative conductivity for various types of surface. The best type of surface for surface-wave transmission is sea water; this accounts for the fact that relatively long-distance radio contacts have been established across the ocean. The electrical properties of the underlying terrain that determine the attenuation of the surface-wave field intensity vary little from time to time, and therefore, this type of transmission has relatively stable characteristics.

Table II. Propagation Characteristics of Local Terrain

Type of surface	Relative conductivity	Dielectric constant
Sea water	Good	80
Large bodies of fresh water	Fair	80
Wet soil	Fair	30
Flat, loamy soil	Fair	15
Dry, rocky terrain	Poor	7
Desert	Poor	4
Jungle	Unusable	--------

b. The surface-wave component generally is transmitted as a vertically polarized wave, and it remains vertically polarized at appreciable distances from the antenna. This polarization is chosen because the earth has a short-circuiting effect on the electric intensity of a horizontally polarized wave but offers resistance to this component of the vertical wave. The ground *currents* of the vertically polarized surface wave do not short-circuit a given electric field but rather serve to restore part of the energy used to the following field (fig. 23). The better the conducting surface, the more energy returned and the less energy absorbed. Since no surface is a perfect conductor or perfect ground (one returning all of the energy) the loss retards the grounded edge of any given wave front, causing it to bend forward in the direction of travel so that the successive wave fronts have a forward tilt (fig. 23). The conducting surface of the earth is then, in effect, a part of a waveguide, and the tilt has the effect of propagating the energy in the direction of wave travel. Poor conducting surfaces cause high loss and greater tilt and, finally, total absorption of the energy. Table III shows the variation in angle of tilt from the vertical for frequencies from 20 kc (kilocycles) to 20 mc, propagated over sea water and over dry ground. As frequency increases, the angle of tilt increases. At 20 mc, the tilt is negligible over sea water, being little more than 1°, but over dry ground it is 35°, effecting a considerable change in polarization.

This tilting of the electric vector of an electromagnetic wave is not to be confused with the bending of a wave, or diffraction, which is a phenomenon associated with a wave front striking the edge of a solid object, the greatest bending taking place at the *lowest* frequencies.

Table III. Angle of Tilt Versus Frequency

Frequency (mc)	Angle of tilt over sea water	Angle of tilt over dry ground
0.02	0°2.5′	4°18′
.20	0°8′	13°30′
2.00	0°25′	32°12′
20.00	1°23′	35°

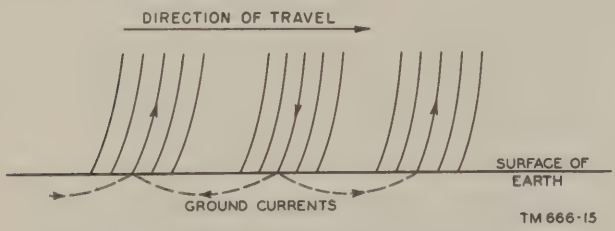


Figure 23. Tilting of electric vector of wave front.

16. Frequency Characteristics of Ground Waves

a. The frequency characteristics of the ground wave determine in large part the particular component of the wave that will prevail along any given signal path. When the conductivity of the earth is high and the wave frequency below 30 mc, the surface wave is the predominant component, except in the case of plane-to-plane or plane-to-ground transmission, in which the direct wave and ground-reflected waves are the principal means of communication. At frequencies greater than 10 mc and less than 30 mc, the dielectric constant of the terrain determines the surface-wave transmission characteristics, the signal being largest for the higher dielectric constants and for the lower frequencies. At frequencies greater than 30 mc, the losses suffered by the surface wave become so excessive that transmission is usually possible only by means of the direct wave. However, at frequencies where the ground-wave field intensity is largely determined by the surface-wave component, vertically polarized radiation is superior to horizontally polarized radiation, except in heavily wooded or jungle areas. In such areas, horizontal polarization provides better gain, even at distances and frequencies where the surface-wave component normally would predominate, because most of the foliage grows vertically and absorbs vertically polarized energy. Above 30 mc, where the direct wave is the predominant component, the difference between vertical and horizontal polarization is negligible.

b. These variations of the ground-wave components with frequency may be summarized, as follows:

(1) The low-frequency band (0.03 to 0.3 mc) is used for moderate-distance ground wave communication. In this band, the ground losses of a vertically polarized wave are small, and the wave is able to follow the curvature of the earth for several hundred miles.

(2) The medium-frequency band (0.3 to 3 mc), which includes the standard broadcast frequencies—amplitude modulation—is used for moderate-distance communication over land and for long-distance communication over sea water up to 1,000 miles.

(3) The high-frequency band (3 to 30 mc) is used for short-distance communication. At these frequencies, the dielectric constant of the earth plays a greater part in the decrease of surface-wave field intensity and is the chief factor causing attenuation at very-high frequencies.

(4) The very-high-frequency band (30 mc and over) is used for line-of-sight communication. At these frequencies, the direct-wave component is increasingly important. The direct-wave range therefore can be extended greatly by increasing the height of transmitter and receiver antennas. Thus, it should be noted that whereas the distance range of the ground wave at low frequencies can be effectively increased only by increasing radiation power, the distance range of frequencies of 30 mc and higher can be effectively increased by increasing antenna heights as well as by increasing radiation power.

17. Tropospheric-Wave Component

a. The tropospheric wave is that component of the entire wave front which is refracted in the lower atmosphere by relatively steep gradients (rapid changes in respect to height) in atmospheric humidity and sometimes by steep gradients in atmospheric density and temperature. At heights

of a few thousand feet to a mile or so, huge masses of warm and cold air exist near each other, causing abrupt temperature differences and changes in density. The resulting tropospheric refraction and reflection make communication possible over distances far greater than can be covered by the ordinary ground wave. A of figure 24, shows the downward bending of a wave front which enters a layer of air the dielectric constant and moisture content of which decrease with height above the surface of the earth; B of figure 24 shows the upward bending of the same wave for the opposite condition. Since the amount of refraction increases as the frequency increases, tropospheric refraction is more effective at the higher frequencies, providing interesting communication possibilities at 50 mc and above.

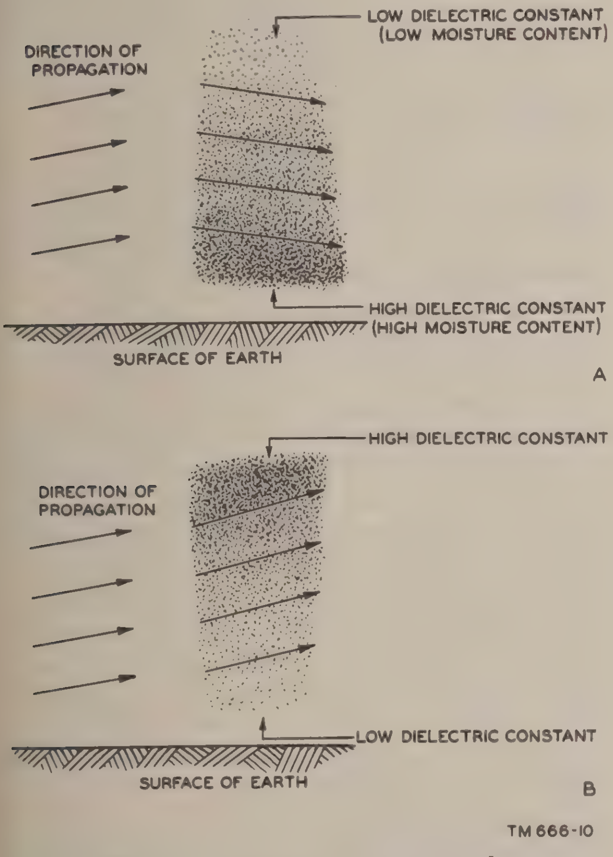


Figure 24. Refraction in the troposphere.

b. One common cause of tropospheric refraction is temperature inversion. Temperature inversion results from several causes—a warm air mass overrunning a colder mass; the sinking of an air mass heated by compression; the rapid cooling of surface air after sunset; and the heating of air above a cloud layer by reflection of the sun's rays from the upper surface of the clouds. Tropospheric-propagation effect depends on weather conditions, and since these vary from minute to minute, they can cause fading or variable field intensity. In tropospheric-wave communication, the receiving and the transmitting antennas should have the same type of polarization, since the tropospheric wave maintains essentially the same polarization throughout its travel.

18. Abnormal Effects of the Troposphere

a. Propagation characteristics of the troposphere vary under special weather conditions, and in some parts of the world such conditions may prevail over long periods. In the tropics and over large bodies of water, temperature inversions are present almost continuously at heights up to 3,000 feet, particularly in the range from 100 to 500 feet. When the boundary of the inversion is defined sharply, waves traveling horizontally or at very low angles of elevation become *trapped* by the refracting layer of air and continue to be bent back toward the earth. Figure 25 shows how such a trapped wave follows a *duct,* the upper and lower walls of which are formed by the boundary and the earth. The waves are guided along within this duct in much the same manner as in a metallic waveguide, and since attenuation in a waveguide is slight, the energy does not fall off inversely as the square of the distance. Thus, the waves follow the curvature of the earth for distances far beyond the optical horizon of the transmitter, and in some localities may consistently reach distances of many thousands of miles.

b. Tropospheric ducts also are formed by the waveguiding effect of two layers of air with sharply defined temperature inversions. The refraction from the upper boundary bends the wave down, and the refraction from the lower boundary bends the wave up, effectively trapping the energy within the layer. The height of the duct determines the minimum frequency, and if this height is only a few feet above the surface of the earth, or from boundary to boundary, transmission may be possible only at the ultrahigh or superhigh frequencies. Occasionally, the height and the dielectric characteristics of the layer are suitable for vhf transmission. However, a necessary feature of duct transmission is that the angle of approach of the incident wave be approximately half a degree or less in order for the wave to be trapped. In addi-

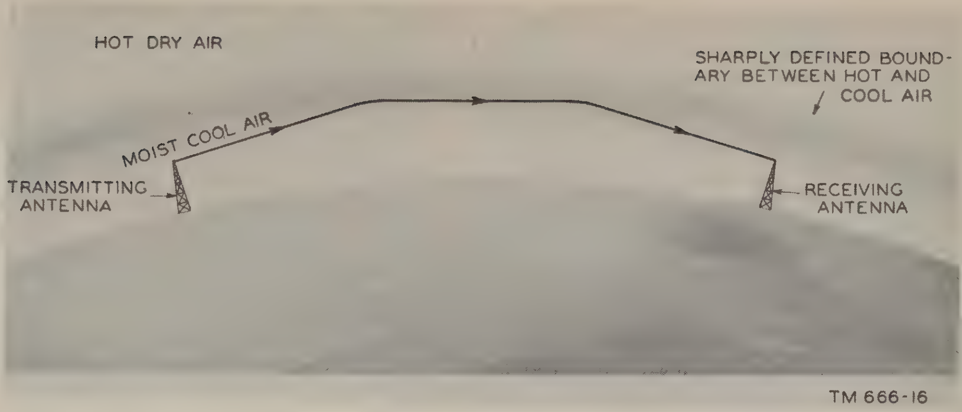


Figure 25. Transmission by means of tropospheric duct.

tion, both the transmitting and the receiving antennas must be *inside* the duct, if communication is to be established by this means. A transmitting antenna *above* the duct, as on a tower or promontory, will not operate into the duct, and no signals by this means will be received at the receiving antenna. Moreover, a receiving antenna *below* a duct will receive no signals from an airplane flying in or above the duct, even though line-of-sight conditions prevail.

Section II. THE IONOSPHERE

19. General

In the early days of radio, mathematical physicists reasoned that it would be impossible to receive radio signals at very great distances because of the attenuation resulting from the absorption of the energy by the earth. When it was found experimentally that signals could be received across the Atlantic Ocean, the work of the physicists was questioned. Their result was correct, of course, for the problem to which it applied—namely, the propagation of ground waves around a curved earth surrounded by free space, as has been noted in the section of ground waves. Obviously, some other means of propagation had to exist. The experimental evidence of trans-Atlantic communication proved only that the assumption of an earth surrounded by nothing but free space was unjustifiable in this connection. It was then suggested by both Heaviside and Kennelly, the one an English scientist and the other an American, that the earth actually is surrounded by an electrified layer which acts as a reflector and prevents the escape of the wave into free space by bending it back toward the earth. Such a layer also could form the source of the electric currents in the upper atmosphere which had been suggested as the cause of changes in the magnetic field of the earth during magnetic storms. Later, when it was shown that not only one, but several such layers actually did exist, and that these layers consisted of ionized gases of the atmosphere, the name *ionosphere* was suggested for the region in which the layers were found.

20. Formation of Ionosphere

As indicated in figure 13, the earth's atmosphere extends up to a distance of over 250 miles. However, the density of the gases that compose this atmosphere decreases with height, so that above 250 miles the air particles are so rare as to be practically nonexistent. Also indicated in figure 13 is the constant state of bombardment to which the atmosphere is subjected by radiation and particle showers from the sun, and by cosmic rays, the source of which is not yet known. The radiation from the sun includes not only the light rays that we see, but also all the components of the entire spectrum, ranging from infrared rays to ultraviolet rays, and particle showers composed of positrons and electrons moving at almost the speed of light. As these different forms of radiation approach the atmosphere of the earth, they reach certain critical levels where the gases are of such density as to be particularly susceptible to ionization by their action, and at these levels ionized layers are formed. The upper layers of air appear to be affected most by particle radiation, although the predominant source of ionization is the ultraviolet

radiation. To understand how this ionization takes place, a brief review of the mechanics of gases is necessary.

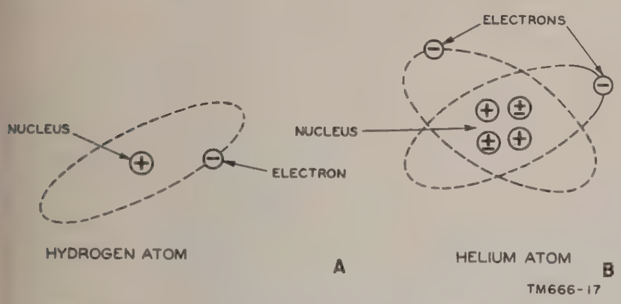


Figure 26. Structure of hydrogen and helium atoms.

a. Matter. All matter (solids, liquids, and gases) is made up of fundamental units called molecules. The molecule, the smallest subdivision of a substance that exhibits all its characteristic properties, is constructed of *atoms* of the elements comprising the substance.

(1) The atom is made up of a central part called the nucleus, around which minute particles or charges of electricity called electrons circulate (fig. 26), somewhat as the planets revolve around the sun. In the normal or neutral atom, the electrical charge of each electron is balanced by an equal charge of opposite kind associated with the nucleus. The kind of charge represented by the electron is conventionally called negative, and that associated with the nucleus is called positive.

(2) In the atoms of many substances, such as gases, one or more of the outer electrons are bound so loosely to the nucleus that they can be detached from the atom by suitable means, thus leaving the atom as a whole with a net positive charge. When this occurs, electrical activity becomes evident.

b. Ionization. It has been found that energy in the form of electromagnetic radiation is capable of dislodging some of the loosely bound electrons from their atoms, provided that the radiation is of the proper wavelength and energy. When a number of such events happens in any gas, the gas is said to be *ionized*, since it has atoms lacking their normal quota of electrons, and free electrons unassociated with any atom. Atoms lacking in their normal quota of electrons are called *positive ions*, and electrons unassociated with any atom are called *negative ions*. The term *ion* is, in fact, applied to any elemental particle that has an electric charge.

(1) Although a few ions may exist in any gas, external energy must be applied to the atom in order to produce an abundance of ions. A state of ionization is said to exist when all or a large proportion of the particles in the gas are positive and negative ions. The external energy necessary for ionization can come from several sources, the most important being from an impact with another particle, from cosmic waves such as light waves, X-rays, gamma rays, and ultraviolet rays; from chemical reaction, or by the application of heat.

(2) The natural ionization in air caused by any of the energies listed above produces approximately 2 ions per cubic centimeter per second at atmospheric pressure. At higher altitudes such as in the ionosphere, the rate of ionization is approximately 100 times as great. In the upper atmosphere, where the pressure is low, conditions are excellent for ionization to take place. The sun constantly gives off ultraviolet rays of the proper wavelength to ionize the gas particles of the upper atmosphere.

c. Recombination. The atoms and ions in a gas are in constant motion, and frequent collisions take place between them. When an electron collides with a positive ion, it may combine with the ion and form again a neutral atom of the gas. The process of recombination goes on constantly, so that an atom, once it has been ionized, does not remain so indefinitely. The time that it takes for recombination, or deionization, depends on several factors, but principally on the average distance between the particles of the gas. If only a few particles are present, as in the upper atmosphere, collisions will not occur very frequently, and the particles remain ionized for relatively long periods.

d. Source of Ionization—the Sun. Although the sun is composed of the same elements that are to be found on the earth, these elements exist in such a violent state of solar activity as to remain constantly in a molten or gaseous state. Probably because of intense internal stresses and the play of atomic forces on a gigantic scale, the sun constantly emits huge amounts of energy in the form of heat, particles, and electromagnetic waves.

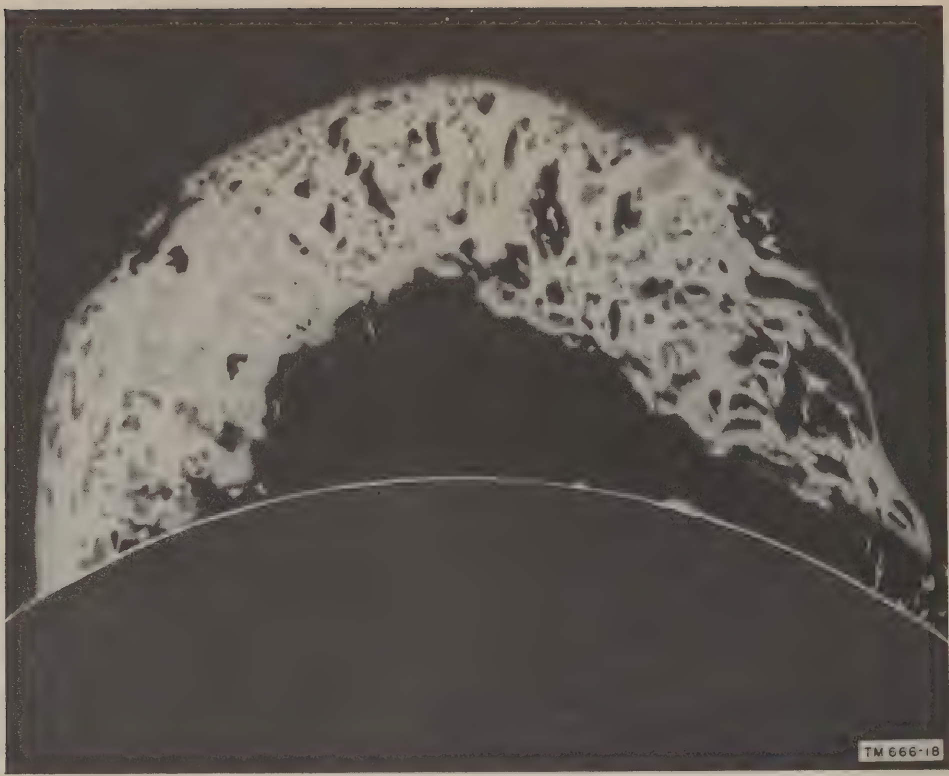


Figure 27. Solar eruption.

Eruptions at the surface of the sun have been noted to shoot immense clouds of hot gases to distances of half a million miles above the surface (fig. 27). Another disturbance of the sun's surface is the appearance of sunspots, which have particular effects on the amount of ultraviolet radiation, and hence on the extent of ionization caused by this radiation.

(1) *Effect of sunspots.* During periods of high sunspot activity, the extent of ionization of the various layers is greater than the average. The sunspots are dark areas

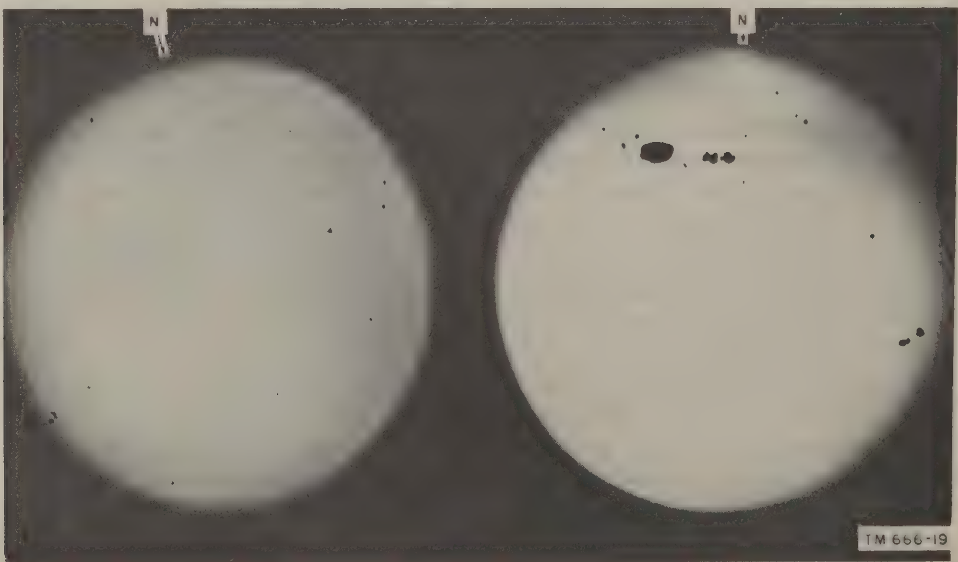


Figure 28. Sunspots.

which appear on the disk of the sun (fig. 28), and although their relative darkness would seem to indicate lower temperatures and lower ultraviolet radiation, they have bright gaseous clouds about them, and the processes involved in the formation of the sunspots probably produce vast amounts of ultraviolet energy. The sunspots usually appear in groups, and follow a more or less definite cycle of activity, with an average time interval of 11.1 years between the maxima of two consecutive cycles. Magnetic storms on the earth also are related to the presence of large sunspots.

(2) *Dellinger fade.* Bright visible flares on the sun's disk instantaneously produce great effects on the ion density of the various ionospheric layers. This effect is known as the Dellinger fade, or sudden atmospheric disturbance. Great increases are noted in the ionization produced at low levels of the ionosphere as the result of these flares.

e. Formation of an Ionized Layer. When ultraviolet radiation of a particular wavelength enters the earth's atmosphere from above, the waves penetrate to a depth at which the critical density of the medium is sufficient to absorb the larger portion of the incident energy in the process of producing ionization. Before reaching this depth, the air particles are dispersed so sparsely that only a relatively few molecules of the rarefied gases become ionized. Upon reaching the level of critical density, a greater proportion of molecules are ionized, but the wave energy becomes so attenuated by the process of ionization that it is too weak to produce further ionization. The higher the frequency of the waves, the further they will penetrate the atmosphere before reaching this level of critical density. Thus, an ionized layer is formed with the greatest intensity of ionization at its center and lesser intensities at its edges. However, both the greater rate of recombination and the attenuation of the waves serve to decrease the extent of ionization in the lower or atmospherically denser part of an ionized region.

21. Ionosphere Layers or Regions

By means of ionospheric *sounding*, it has been determined that there are four distinct layers of the ionosphere, which are called, in order of increasing heights and intensities, the *D*, *E*, *F*1, and *F*2 layers. The relative distribution of these layers about the earth is indicated in figure 29. As may be seen in this figure, the four layers are present only during the daytime, when the sun is directed toward that portion of the atmosphere. During the night, the *F*1 and *F*2 layers seem to merge into a single *F* layer, and the *D* and *E* layers fade out, because of the recombination of the ions composing them. *However, the actual number of layers, their heights above the earth, and the relative intensity of ionization present in them all vary from hour to hour, from day to day, from month to month, from season to season, and from year to year.*

a. D Region. At somewhat more than twice the

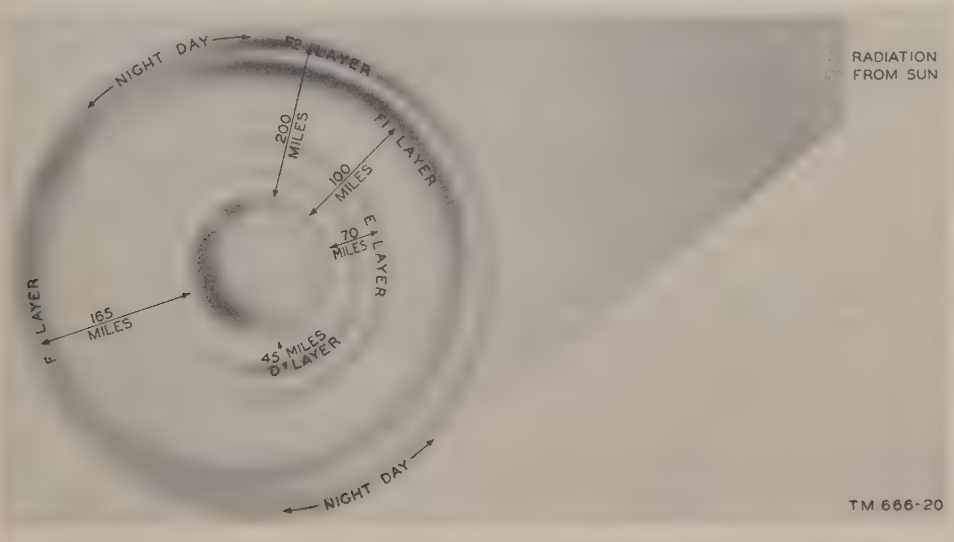


Figure 29. Ionosphere layers and regions.

highest altitude ever reached by man or between heights of 30 to 55 miles (50 to 90 kilometers) above the surface of the earth, is the first region of pronounced ionization, known as the *D* region. In comparison with the conditions existing in the layers at greater heights, the amount of ionization in the *D* region is not extensive and has little effect in bending the paths of high-frequency radio waves. The chief effects of the ionization in this region are to cause a weakening or an attenuation of the field intensity of high-frequency radio waves as the transmission path of such waves crosses through this region, and to cause complete absorption of low- and medium-frequency radio waves. The *D* region exists only during the daylight hours, and its intensity follows the variation of the sun's altitude, becoming most dense at noon, and fading out shortly after sunset because of the rapid recombination of ions at this atmospheric height. It is chiefly responsible for the fact that the intensity of high-frequency waves is lower when the transmission path lies in sunlit hours than when the path traverses these regions during darkness.

b. E Layer. At heights between 55 and 90 miles (90 to 145 km) lies the second region in order of height, called the *E* layer. This layer sometimes is known as the Kennelly-Heaviside region after the names of the men who first proposed its existence. The layer height varies somewhat with the season, lower heights occurring when the sun is in that latitude, probably because the solar ultraviolet radiation penetrates farther into the earth's atmosphere when the sun is more directly overhead. Since the rate of recombination is large at this atmospheric level, the intensity of ionization of the *E* layer follows the sun's altitude variations closely, reaching a maximum at about noon, and fading to such a weak level during the night as to be practically useless as an aid to high-frequency radio communication. The number of electrons per unit volume in this layer is usually great enought to refract back to earth radio waves at frequencies as high as 20 mc. Thus, the *E* layer is of great importance to radio transmission for distances less than approximately 1,500 miles. For longer distances, transmission by this means is rather poor, because the necessarily low vertical angle of departure of the wave from the ground results in greater absorption of the wave in the ionized region. At distances greater than 1,500 miles, better transmission can be obtained by means of the *F*, *F*1, and *F*2 layers.

c. F Layer. At heights between 90 and 240 miles (145 to 380 km) above the earth's surface is another region of ionization, known as the *F* layer. Ionization exists at all hours, usually with two well defined layers during the daytime and one during the night. *In this region, at night,* the single *F* layer lies at a height of about 170 miles, or 270 km. The atmosphere is so rare at these heights that recombination of ions takes place at a very slow rate, and sufficient ions remain throughout the night to refract high-frequency waves back to earth.

d. F1 and F2 Layers. During the daylight hours, especially when the sun is high, as in tropical latitudes and during summer months, the *F* region splits up into two distinct layers—the *F*1, with a lower limit at a height of approximately 90 miles (145 km), and the *F*2, with a lower limit at a height of about 160 to 220 miles, depending on the seasons and the time of day. The *F*2 layer is the most highly ionized of all the layers and is the most useful for long-distance radio communication. The degree of ionization for this layer exhibits an appreciable day-to-day variation in comparison with that of the other layers. The intensity of ionization reaches a maximum in the afternoon and gradually decreases throughout the night. The rise of ion density is very rapid in the morning, and the low recombination rate permits this high ion density to persist.

e. Other Layers. In addition to these regions of ionization which appear regularly and undergo variations daily, seasonally, and from year to year in height and ionization, other layers occasionally appear, particularly at heights near that of the *E* layers, much as clouds appear in the sky. Frequently their appearance is in sufficient intensity to enable good radio transmission to take place by means of reflection from them. At other times, especially during disturbed conditions in polar regions such as those that cause the aurora borealis, diffuse ionization may occur over a fairly large range of heights and may be detrimental to radio transmission because of the excessive absorption produced.

22. Ionosphere Characteristics

Although a detailed analysis of what happens to electromagnetic waves as they enter the ionosphere is beyond the scope of this manual, the principal factors and assumptions are described in this paragraph in terms of practical effects.

a. Critical Frequency. In addition to the height,

the principal ionosphere characteristic which controls or determines long-distance radio transmission is the ionization density of each of the layers. The higher the frequency, the greater the density of ionization required to reflect waves back to earth. In other words, the shorter the length of the waves, the denser or more closely compacted must be the medium to refract them. Therefore, the upper layers, which are the most highly ionized, reflect the higher frequencies, whereas the *D* layer, which is the least ionized, does not reflect frequencies above approximately 500 kc. Thus, at any given time, *for each layer* there is a value of highest frequency, called the *critical frequency*, at which waves sent vertically upward are reflected directly back to earth. Waves of frequencies higher than the critical frequency pass on through the ionized layer and are not reflected back to earth, unless they are reflected from an upper layer. Waves of frequencies lower than the critical frequency are reflected back to earth, unless they are absorbed by, or have been reflected from, a lower layer.

(1) Figure 30 shows waves of different frequencies radiated vertically into the ionosphere. Two of these signals are returned directly to the earth and the third passes through both layers and is not returned. Each of the returned waves is at the critical frequency for its layer—that is, the highest frequency that is returned. All frequencies below the critical frequency are returned in the same manner. The unreturned signal is at a frequency above the critical frequency for either layer and therefore passes through to outer space.

(2) This phenomenon may be understood in terms of the combined refractive and reflective effects of ionization on an electromagnetic wave. When a ray, or train of waves, enters an ionospheric layer, it is slowed down as soon as it starts to penetrate the layer. This process of refraction is similar to that of the refraction of light passing from air to water, as explained in paragraph 9. When the signal enters the ionosphere at a 90° angle, there is no bending of the wave—the whole wave front is slowed

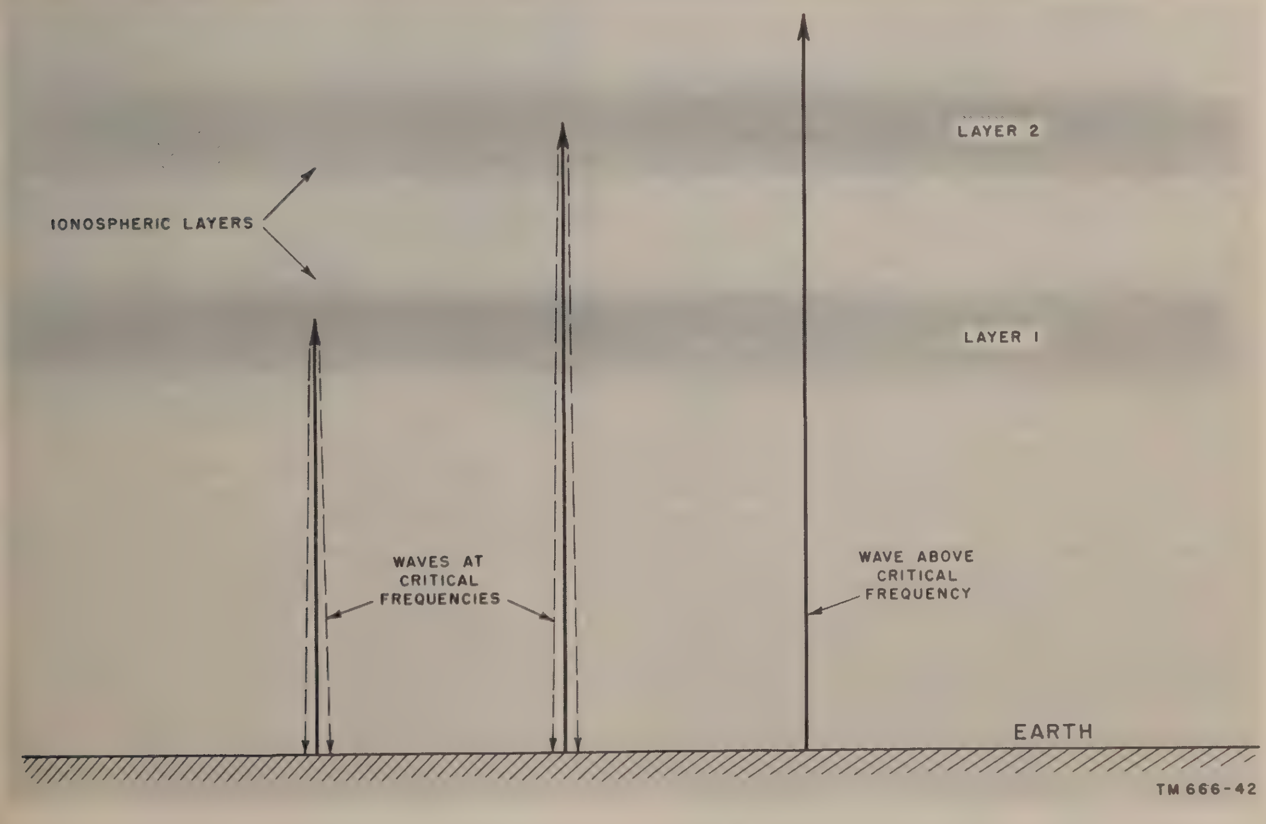


Figure 30. Critical frequencies.

down uniformly. The higher the frequency of the signal, the deeper it must penetrate the layer before it surrenders all of its energy. It should be remembered, however, that an ionization layer is most dense near its center, and that the wave will pass on through if this center density is insufficient to absorb all of the energy. The surrendered energy is reradiated by the layer, directly downward to the area of transmission. By analogy, this effect is similar to that obtained in tossing tennis balls vertically upward to a wire screen. If the openings in the screen are smaller than the diameter of the ball, all of those thrown are reflected back almost as effectively as though the screen were a solid piece of metal. But if golf balls were thrown at the same screen, most of them would pass through the screen and not be reflected. Thus, it may be concluded that (like frequency in respect to ionization) there is for a given screen a critical diameter of ball which will be reflected back; any smaller ball will pass on through.

b. Critical Angle. The determination of a critical frequency by vertical propagation is useful because it marks a boundary condition. Electromagnetic waves used in radio communications, however, are generally incident at some oblique angle to the ionosphere. These waves are refracted by the ionosphere and may or may not be returned to the earth. Obviously, any frequency at or below the critical frequency will be returned to the earth, but frequencies above the critical frequency *also* will be returned if propagated at certain angles of incidence. This effect can be understood by considering for a moment our former analogy of the screen and the tennis balls. If, for instance, the critical diameter for a given screen is the diameter of a tennis ball, then *golf balls* thrown obliquely at the screen will hit the wire mesh at an angle and be reflected downward, even though they would pass easily through the screen if thrown vertically upward. Thus, for this screen there is a certain angle of incidence at which most of the golf balls would be reflected downward. In electromagnetic-wave propagation the same conditions prevail. At angles of incidence near the vertical, a given frequency passes on through the ionosphere. But as the angle lessens, a point is reached at which the wave is reflected back to earth. This angle is called the critical angle. The point at which the wave returns is a *minimum* distance, called the *skip* distance; at smaller angles of incidence, the wave returns at greater and greater distances.

(1) The concept of critical angle may be understood by consideration of a similar optical phenomenon (fig. 31). If a beam

Figure 31. Critical angle of light beam.

of light passes from a dense medium (water) to one of less density (air) at right angles to the boundary between them, it passes through with no change in direction. As the angle of incidence becomes smaller than 90°, the beam is only slightly reflected back into the water, most of the light being refracted or bent in the air. The amount of bending increases as the angle grows smaller, but at a given angle, which is the critical angle, *no* light is re-

fracted by the air, *all* of it being reflected back into the water. At angles smaller than the critical angle, the light beam is reflected back at greater and greater distances from the source. At this point, it should be noted that this optical phenomenon cannot be applied strictly to radio waves, since the boundaries between the dense ionization of the layer and the air above it are not sharp boundries. The wave is both bent and reflected, and therefore, in propagation work the terms *refraction* and *reflection* tend to be used interchangeably.

(2) The popular explanation of the return of radio waves as a phenomenon in refraction alone is illustrated in figure 32.

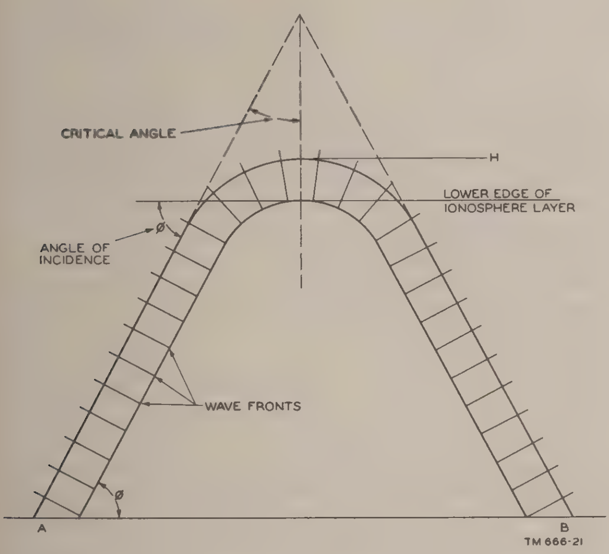


Figure 32. Idealized refraction of radio wave.

Suppose a train of wave fronts to be propagated from A so that it enters the ionosphere at an angle, Ø. As each wave front enters the ionosphere, the upper part of the wave front feels the effect of lowered index of refraction first. Therefore, the upper part of each wave front has an increased phase velocity, so that the entire wave front as it enters the ionosphere wheels about like a column of soldiers obeying the command, "Column right." Since the central parts of the ionosphere have a greater ion density, the bending effect on the upper part of the wave front is greatest, so that the wheeling process continues and the waves are directed back toward the earth at point B.

c. Virtual Height. The oversimplified curved path shown in the figure also helps to make clear the notion of virtual height of an ionospheric layer. In following the curved path, as illustrated in the schematic drawing of figure 33, the time of

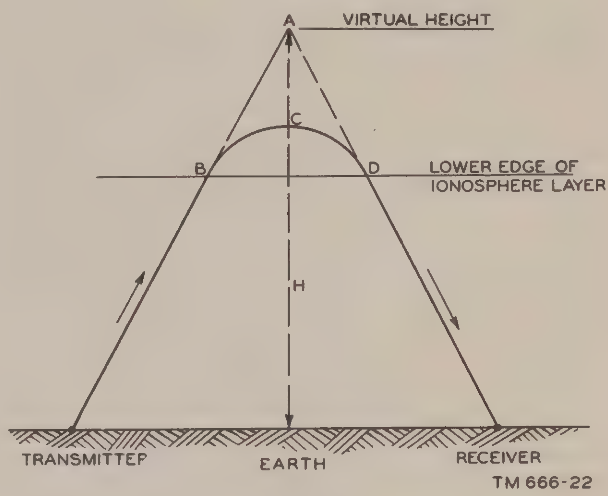


Figure 33. Virtual height of ionospheric layer.

transmission of the radio wave along the actual path *BCD* in the ionized layer is considered to be the same as would be required for transmission along path *BAD* if there were no ionized particles present, and a perfect reflecting surface at A instead. The height, H, from the earth to the intersection of the two projected straight parts of the path is called the virtual height of the layer. Note that this virtual height is considerably greater than the actual layer height. However, it is a convenient and an important quantity in measurements and applications involving ionospheric reflections.

23. Regular Variations of Ionosphere

a. General. Since the existence of the ionosphere is dependent on radiations from the sun, it is obvious that the movements of the earth about the sun, or changes in the sun's state of activity which might serve to cause an increase or decrease in the amount of its radiation, will result in variations in the conformation of the ionosphere. These variations include those which are more or less regular in their nature and, therefore, can be predicted in advance, and the irregular variations resulting from the abnormal behavior of the sun. For pur-

poses of discussion, the regular variations may be divided into four classes: the diurnal or daily variation, the seasonal, the 11-year, and the 27-day. For convenience, table IV lists the regular variations together with the resulting effects upon the ionosphere and on radio communications, and also gives suggestions that may be followed in compensating for these effects.

Table IV. Regular Variations of Ionosphere

Type of variation	Effect on ionosphere	Effect on communications	Method of compensation
Diurnal (variation with hour of day).	*F layer:* Height and density decrease at night, increase after dawn. During day, layer splits into—(1) *F1* layer: Density follows vertical angle of sun; (2) *F2* layer: Height increases until midday, density increases until later in day. *E layer:* Height approximately constant, density follows vertical angle of sun. Practically nonexistent at night. *D layer:* Appears after dawn, density follows vertical angle of sun, disappears at night.	Skip distance varies in 1- to 30-mc range. Absorption increases during day.	Use higher frequencies during day, lower frequencies at night.
Seasonal	*F2 layer:* Virtual heights increase greatly in summer, decrease in winter. Ionization density peaks earlier and reaches higher value in winter. Minimum predawn density reaches lower value in winter. *F1, E, and D layers:* Reach lower maximum densities in winter months.	MUF's (maximum usable frequencies) (par. 28), generally reach higher midday values in winter but maintain high values later into afternoon in summer. Predawn dip in MUF's reaches lower value in winter. Less absorption encountered in winter.	Provide greater spread between nighttime and daytime operating frequencies in winter than in summer.
11-year sunspot cycle	Layer density increases and decreases in accord with sunspot activity (maximum, 1947–1948 and 1958–1959; minimum 1944 and 1955).	Higher critical frequencies during years of maximum sunspot activity. MUF variation: Sunspot max: 8–42 mc.; sunspot min: 4–22 mc.	Provide for higher operating frequencies to be used during periods of sunspot maximum and lower frequencies for use during minimum. (Consult TB 11–499 to determine MUF.)
27-day (sunspot)	Recurrence of SID's (sudden ionospheric disturbances) and ionospheric storms at 27-day intervals. Disturbed conditions frequently may be identified with particularly active sunspots whose radiations are directed toward the earth every 27 days as the sun rotates.	See effects of SID's and ionospheric storms in table V.	See compensation for SID's and ionospheric storms in table V.

b. Diurnal. For the most part, the diurnal variations and their effects upon the ionosphere layers have been discussed in the description of these layers (par. 21). Note, in table IV, that to compensate for the resulting variations in the skip distance, it is suggested that higher medium frequencies be used during the daytime, and lower medium frequencies at night. The reason for this appears in the fact that the ion density of the *F*2 layer is greater during the daytime, and will reflect radio waves of higher frequency than the *F* layer will reflect during the night. The higher frequency waves suffer less absorption in passing through the *D* region, whereas at night the disappearance of the *D* region permits the use of lower frequencies.

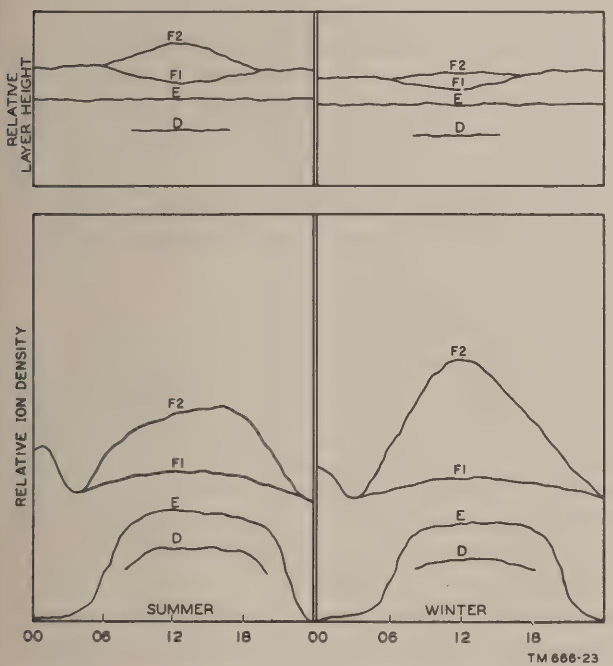


Figure 34. Daily and seasonal variations in ion density.

c. Seasonal. As the apparent position of the sun moves from one hemisphere to the other with corresponding changes in season, the maximum ion density in the *D*, *E*, and *F*1 layers shifts accordingly, each being relatively greater during the summer. The *F*2 layer, however, does not follow this pattern in seasonal shift. In most localities, the *F*2 ion density is greatest in winter and least in summer, which is quite the reverse of what might be expected from simple theory. Figure 34 shows graphs of the relative ion densities of all layers, and also the relative heights of these layers above the surface of the earth, as the seasonal shifts occur. Note that, in winter the ion density of the *F*2 layer rises to a sharp peak at about noon, and assumes a much higher density than in summer. Also, note that the separation of the *F*1 and *F*2 layers is not so well defined in summer, since the height of the *F*2 layer is relatively less during that season.

d. Eleven-year. That sunspot activity varies according to an 11-year cycle has been known since 1851. Shortly after the discovery of this phenomenon, a method was devised for measuring the relative intensity of sunspot activity, and, by means of this method, the alternations from maximum to minimum have been followed closely throughout the years. Briefly, the method entails the use of the so-called Wolf *sunspot number*, a number obtained for each day by multiplying by 10 the number of distinct visible sunspot groups and adding thereto the number of individual spots observable in the groups. For months at a time, the visible surface of the sun may be devoid of spots and so that sunspot number is zero (comparing views shown in fig. 28). This frequently occurs during times of sunspot minima. At other times, even the mean annual sunspot number has been known to rise as high as 140, with daily values running into the hundreds. These conditions occur at the maximum of the sunspot cycle. Although the time from minimum to minimum has been found to be variable, it averages around 11 years. Also, the height of the maximum and the depth of the minimum vary from cycle to cycle. The increased activity at times of sunspot maxima is reflected in an increase in ion density of all the ionosphere layers, resulting in higher critical frequencies for the *E*, *F*1, and *F*2 layers, and higher absorption in the *D* region. This permits the use of higher frequencies for communication over long distances at times of sunspot maxima than would be usable at times of sunspot minima. The increased absorption in the *D* region, which has the greatest effect on the lower frequencies, requires that higher frequencies be used, but the over-all effect is an improvement in propagation conditions during sunspot maxima as the critical frequencies are raised more than the absorption limits.

e. Twenty-Seven Day. Another cycle that is due to sunspot activity is the 27-day variation resulting from the rotation of the sun on its axis. As the number of sunspots changes from day to day with solar rotation or the formation of new spots or the disappearance of old ones on the

visible part of the sun, absorption by the D region also changes. Similar changes are observed in the E layer critical frequency. These variations exhibit wide geographic range; they are not effects that are observed at one station and not observed at others. Although fluctuations in $F2$ layer critical frequencies from day to day are greater than for any other layer, these fluctuations are not generally of a world-wide character. Because of the variability of the $F2$ layer, precise predictions of its critical frequencies cannot be made for individual days, although seasonal and long-term trends and geographic distribution may be outlined accurately in advance. It is necessary in selecting frequencies for long-distance communication to allow for these fluctuations.

24. Irregular Variations of Ionosphere

In addition to the more or less regular variations in the characteristics of the ionosphere, a number of singular, transient effects, though unpredictable, have important bearing on propagation phenomena. Some of the more prevalent of these effects are: sporadic E; sudden ionospheric disturbance (Dellinger fade); ionospheric storms; and scattered reflections. These variations have been listen for convenience in table V where their effects on the ionosphere and on radio communication, together with suggestions for compensating for them, are given.

a. Sporadic E. The sporadic E, also known as the E_s layer, is an ionized cloud that appears at indefinite intervals, and at a slightly greater height than the normal E layer. The nature and cause of this abnormal layer are as yet unknown. Sometimes the sporadic E consists of an extremely efficient radiating surface that is capable of reflecting so much of the energy radiated from the transmitting antenna, even at frequencies of 10 to 15 mc, that reflections from the other layers of the ionosphere are blanked out completely. At other times, the sporadic E may be so *thin* that, although its presence can be verified by *sounding*, reflections from the upper layers easily can be received through it. The sporadic E layer may occur during the day or night. Its occurrence is frequent, and thus, from 25 to 50 percent of the time, long-distance propagation at frequencies up to 15 mc is rendered possible by its means in middle latitudes. Occurrence of sporadic E is not usually simultaneous at all stations. In general, tropical stations exhibit less sporadic E than stations in higher latitudes.

b. Sudden Ionospheric Disturbance or Dellinger Fade. The most startling of all the irregularities of the ionosphere and of radio wave transmission is the sudden type of distrubance manifested by a radio fadeout. This disturbance, abbreviated SID, and sometimes called the Dellinger fade, comes without warning and may prevail for a length of time from a few minutes to several hours. All stations lying wholly or in part on the sunward side of the earth are affected, and, at the onset of SID, receiving station operators are inclined to believe that their radio sets have suddenly gone *dead*. Examination of the sun at the times of occurrence of these effects, however, has revealed that in all cases where reliable solar data were available the appearance of this ionospheric disturbance was coincidental with the onset of a bright solar eruption (fig. 35), and its duration was the same as that of the eruption. Such an eruption causes a sudden abnormal increase in the ionization of the D region, frequently with simultaneous disturbances in terrestrial magnetism and earth currents. Such increases in D region ionization usually result in total absorption, in this region, of all frequencies above 1,000 kc.

c. Ionosphere Storms. An ionosphere storm is a period of disturbance in the ionosphere, during which there are large variations from normal, of critical frequencies, layer heights, and absorption. These storms may last for periods of varying intensity (from several hours to several days), and usually extend over the entire earth. High-frequency sky-wave transmission above approximately 1,500 kc then shows low intensity and is subject to flutter fading. During the first few hours of severe ionosphere storms, the ionosphere is turbulent, stratification is destroyed, and radio-wave propagation is erratic. During the later stages of severe storms and during the whole period of more moderate storms, the upper part of the ionosphere is expanded and diffused. The critical frequencies are much lower than normal because of a decrease in ion density, and the virtual heights of the layers much greater, so that the maximum usable frequencies are much lower than normal. It is often necessary to lower the working frequency to maintain communication during one of these storms. There is also increased absorption of radio waves during the storm. Ionosphere storms are most severe at the higher latitudes and decrease in intensity toward the equator. These

Table V. Irregular Variations of Ionosphere

Type of variation	Effect on ionosphere	Effect on communications	Methods of compensation
Sporadic *E* layer	*Clouds* of abnormal ionization occurring in the *E* layer or slightly above for a large portion of time each month result in abnormally high critical frequencies. Usually spotty in geographic extent and time.	Excellent transmission within normal skip distance. Occasionally, long-distance communications on frequencies of 60 mc or higher are possible.	Frequency may have to be lowered to maintain short-skip communications. At times, long-distance communications on abnormally high frequencies are possible. (See TB 11–499.)
Sudden ionospheric disturbance (SID).	Unusual amount of ultraviolet radiation from solar flare results in abnormally high ionization in all layers. Ionization increase occurs with great suddenness throughout daylight portion of earth.	Normal frequencies above 1 or 1.5 mc are rendered useless because of high absorption in the abnormally-ionized *D* layer. Frequencies considerably higher than normal will survive this absorption for short hops. Low frequencies may not penetrate the *D* layer and thus may be transmitted for long distances.	Raise working frequency above normal for short-hop transmission. Lower frequency below normal for long-hop transmission.
Ionospheric storm	Usually accompanies magnetic disturbance occurring about 18 hours after SID's. Probably both are due to abnormal particle radiation. Upper ionosphere expands and diffuses, critical frequencies below normal, virtual heights above normal. Severest effects toward geomagnetic poles, decreasing toward equator. Few minutes to several hours in duration; effects disappear gradually in few days.	Limits number of usable high frequencies.	Use frequencies lower than normal, particularly in high latitude circuits.
Scattered reflections	The ionospheric layers are not smooth. Irregularities in density and in height are normal.	Because of irregularities in the ionosphere, the electric field at a receiver consists of several fields arriving from slightly different directions with varying phase relationships. The result is fading of the signal resulting from cancelation and reinforcement.	Fading of short duration. No compensation required.

storms probably are caused by abnormal particle radiation from the sun, and are likely to occur during periods of great solar activity. The storms are most likely to start about 2 days after an active sunspot group crosses the center of the sun's disk.

d. Scattered Reflections. An irregular type of reflection from the ionosphere occurs at all seasons and is prevalent both day and night. The ionosphere layers are irregular, and the presence of ionized clouds or scattering patches at *E* layer heights has been mentioned previously. Irregular reflections are obtained from these because of the rapid change of ionization with height. A radio wave can reflect from either the top or bottom of one of these scattering clouds, and these reflections make possible the reception of signals within the normal skip zones and at frequencies much higher

Figure 35. Bright solar eruption.

than those well receivable from the regular layers. The reflections may cause signal distortion and contribute to so-called flutter fading. Signals received from such reflections either may arrive from all directions or, if the transmitter operates with a highly directional antenna, may appear to come from the direction in which the antenna is pointed. The field intensity at the receiving station may be the sum of the components of several contributing radio waves of varying phase relations. Figure 36 shows the effect of just two of these scattered signal components arriving at a receiving station by different paths, the one by reflection from the lower surface of the scattering cloud of ionization, the other after re-reflection from the top of this same cloud. It is obvious that, with respect to the latter signal component, a time lag will occur which either will serve to cancel a portion of the signal reflected directly from the bottom surface of the scattering cloud, and thus cause fading, or will augment this signal, depending upon the phase relations of the two components at the receiving station.

25. Ionosphere Predictions

By *sounding* the ionosphere it is possible to predict for several months in advance the various important characteristics of the ionosphere above any point on the surface of the earth. Such predictions are useful in the selection of optimum frequencies for radio communication over a definite path at particular times. The average variations of the critical frequency and maximum usable frequency factors are sufficiently well known to permit long-range predictions to be made for average conditions on ionospherically quiet

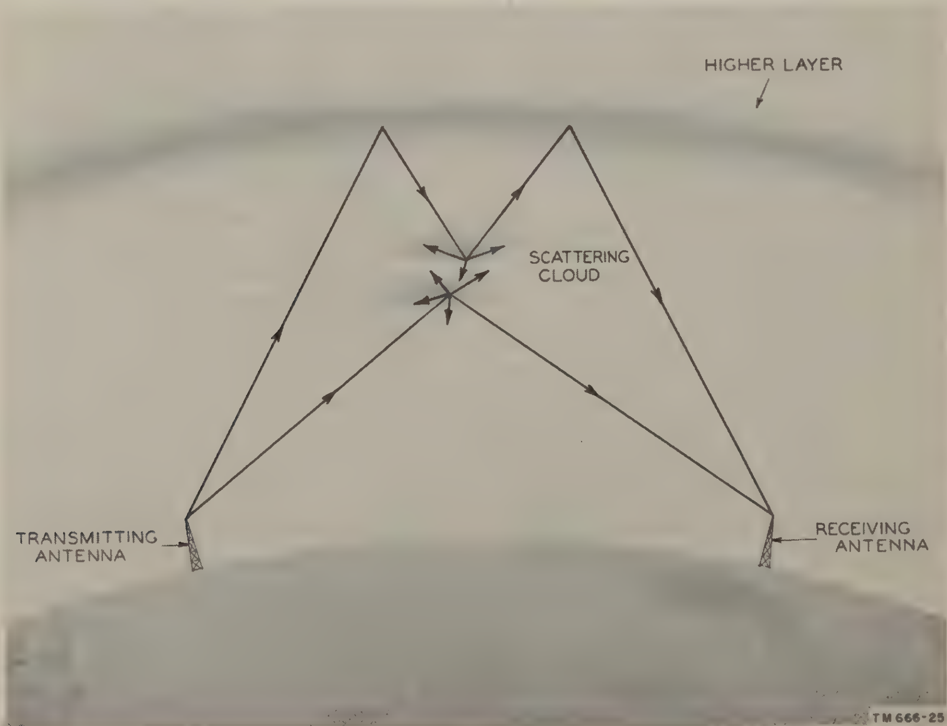


Figure 36. Scattering of signal components of radio wave.

days (days without ionosphere disturbances). One of the basic principles employed in all ionosphere predictions is the relation of ionospheric characteristics to the sunspot cycle. The actual prediction consists essentially of first predicting the solar activity and then deducing, from the mass of data available, the corresponding trends of seasonal, diurnal, and geographic variations of the ionosphere characteristics. No attempt is made at present in these long-range predictions to estimate the detailed day-to-day variations in the ionosphere, these being rather localized and depending on conditions of solar radiation and terrestrial effects of the particular days. Also, no account is taken of ionospheric disturbances, either of the ionosphere-storm type or of the sudden ionosphere-disturbance type. These abnormalities constitute a different forecasting problem. Regular predictions now are published monthly, for a period of 3 months in advance, as TB 11-499-( ), Basic Radio Propagation Predictions.

Section III. SKY-WAVE PROPAGATION

26. General

Sky-wave propagation refers to those types of radio transmission that make use of ionospheric reflections to provide signal paths between transmitters and receivers. Sky-wave transmission, being by far the most important method for long-distance radio communication, presents many problems that can be solved adequately only through a complete understanding of the principles involved. A typical question in sky-wave propagation is whether the ionosphere will support (reflect) a radio wave of a particular frequency and whether the received signal will be strong enough at the receiver to be heard above the noise level present at the receiver. The answer to this question can be given only after considering the many factors involved—what particular path the radio wave will take in traveling from transmitter to receiver, whether the frequency of the radio wave lies between the limits determined by the maximum usable frequency and the lowest useful high frequency for the particular signal path; and the field strength that may be expected of the signal upon its arrival at the receiver (received signal strength).

27. Sky-Wave Transmission Paths

Figure 37 illustrates some of the many possible paths of radio waves from a transmitter to a receiver as transmitted by reflection from an electrically conducting layer of the ionosphere. Note that some of the components of the entire wave front, which in this case are assumed to be of too high a frequency for reflection by the ionized layer, pass on through and are lost in outside space, unless they happen to be reflected from some higher layer having a greater degree of ion density. Other components of the wave, which are assumed to be of the correct frequency for reflection from the ionosphere layer, are returned to earth, and it is these components of the wave that provide communications. Note also that the *skip distance* is that distance from the transmitter at which the ion density of the layer will just support reflection. The *skip zone* and its relation to the ground wave are shown in figure 38. When the skip distance becomes less than the inner limit of the skip zone, both the sky wave and the ground wave may have nearly the same field intensity but a random relative phase. When this occurs, the field of the sky wave successively reinforces and cancels that of the ground wave, causing severe *fading* of the signal. Note the distinction between the terms *skip distance* and *skip zone*. For each frequency (greater than the critical frequency) at which reflection from an ionosphere layer takes place, there is a skip distance that depends only on the frequency and the state of ionization. The skip zone, on the other hand, depends on the extent of the ground-wave range and disappears entirely if the ground-wave range equals or exceeds the skip distance.

a. Sky-Wave Modes. The distance at which the wave returns to the earth depends on the height of the ionized layer and the amount of bending of the path while traversing the layer, the latter depending on the frequency of the wave as compared to the ion density of the layer required to refract or bend the wave. Upon return to the earth's surface, part of the energy enters the earth, to be rapidly dissipated, but part is reflected back into the ionosphere again, where it may be reflected downward again at a still greater distance from the transmitter. This means of travel in hops, by alternate reflections from the ionosphere and from the surface of the

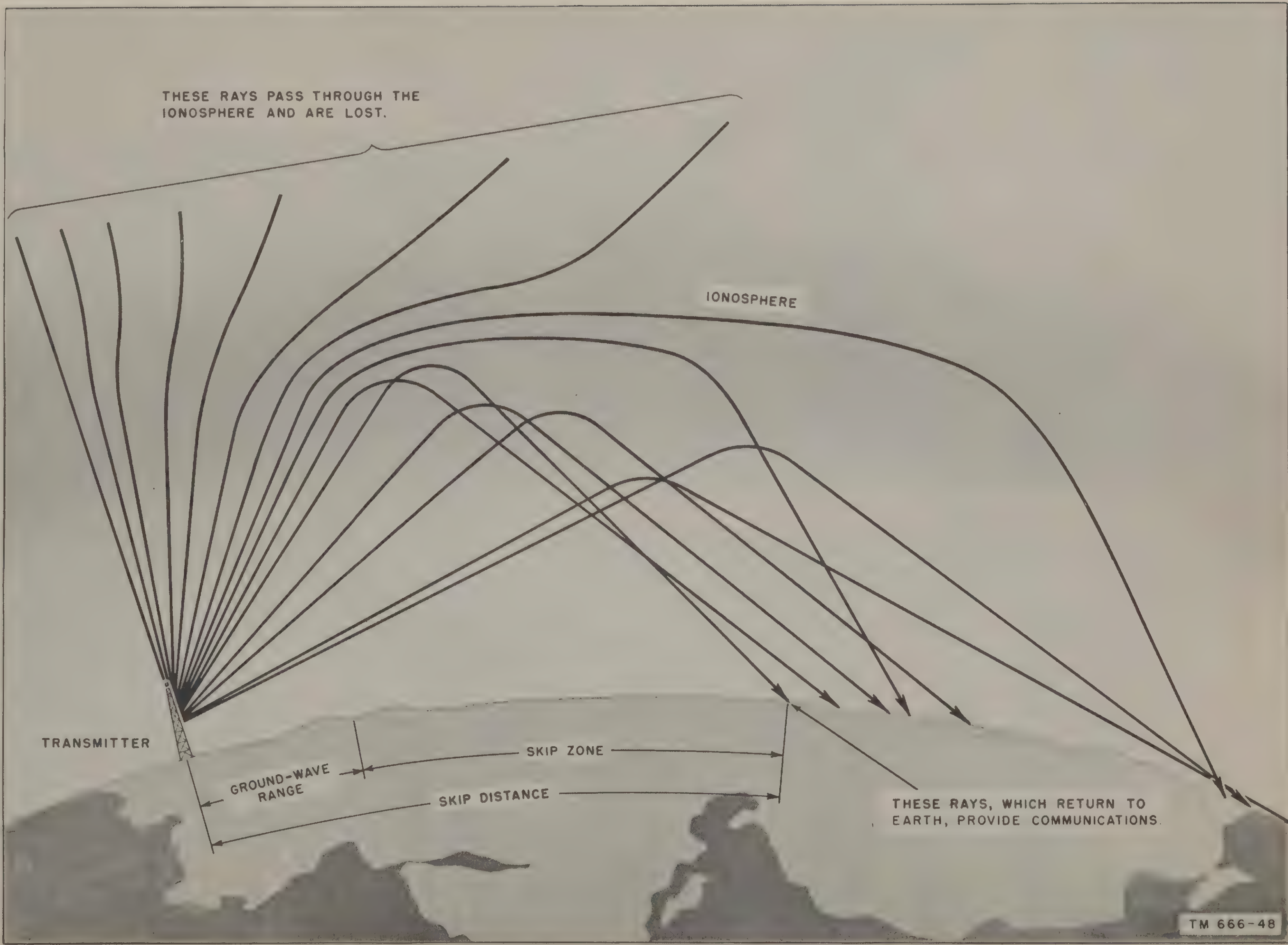


Figure 37. Various sky-wave transmission paths.

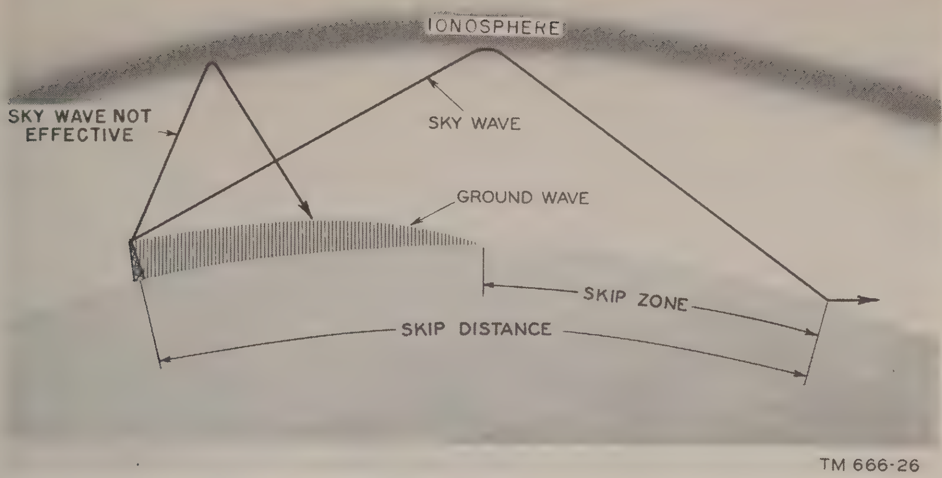


Figure 38. Skip zone.

earth, may continue, and enables transmission to be received at long distances from the transmitter. Figure 39 illustrates this means of travel for paths involving one and two reflections from the ionosphere (single- and double-hop modes). Figure 40 further illustrates this means of travel and reflection from different layers, with the layers represented by lines for simplicity. Figure 40 also relates the heights of the various ionized layers to actual distances along the earth's surface.

b. Great-Circle Path. The paths which the radio waves *normally* traverse in traveling from the transmitter to the receiver lie in the plane passing through the center of the earth and the transmission and reception points. The intersection of this plane with the surface of the earth is the great-circle path between the transmission and reception points. Radio-wave transmission paths which lie in this plane generally are called, for brevity, great-circle paths. Frequently, however, waves do not follow paths confined to this plane, and this deviation is called non-great-circle transmission. The part of the ionosphere which controls sky-wave propagation is the portion directly above the great-circle path. For single-hop transmission, this portion is a region centered above the midpoint of the great-circle path. The situation becomes more complicated when the transmission path is too long for a single hop, and it is necessary to consider ionsphere conditions at more than one point along the path between the transmitter and the receiver. Waves can follow either the major arc or the minor arc of the great-circle path. For instance, radio waves emanated at New York City might travel cross-country, or westward, to reach San Francisco, which would be along the minor arc of the great-circle path between these cities, or these waves might travel eastward, almost around the world to the same destination, which would be along the major arc. The two types of transmission are called *short-path* and *long-path* transmission, respectively.

c. Frequency. As noted previously in the discussion of the ionosphere, the higher the frequency of a wave, the less it is refracted by a given ion density. Thus, if the angle of incidence of the wave with the ionosphere is fixed and the frequency increased, the minimum distance between the transmitter and the point of return of the wave to the earth increases slightly. Figure 41 shows three separate waves of different frequencies entering at the same angle an ionospheric layer of a given density. Here, the 100-mc wave is not refracted sufficiently by the ionosphere and is not returned; the 5-mc and the 20-mc waves are returned, but the 20 mc wave, being refracted less than the 5-mc wave, returns at a greater distance.

d. Incident Angles. For a radio wave of a particular frequency and for an ionized layer of a particular density of ionization, there is an angle of incidence of the wave, called the critical angle, at which the wave is reflected and returns to earth near its minimum or skip distance. This phenomenon is explained in detail in paragraph 22, but it should be noted that the critical angle of a given wave sometimes is defined as the angle at which the wave is propagated horizontally within

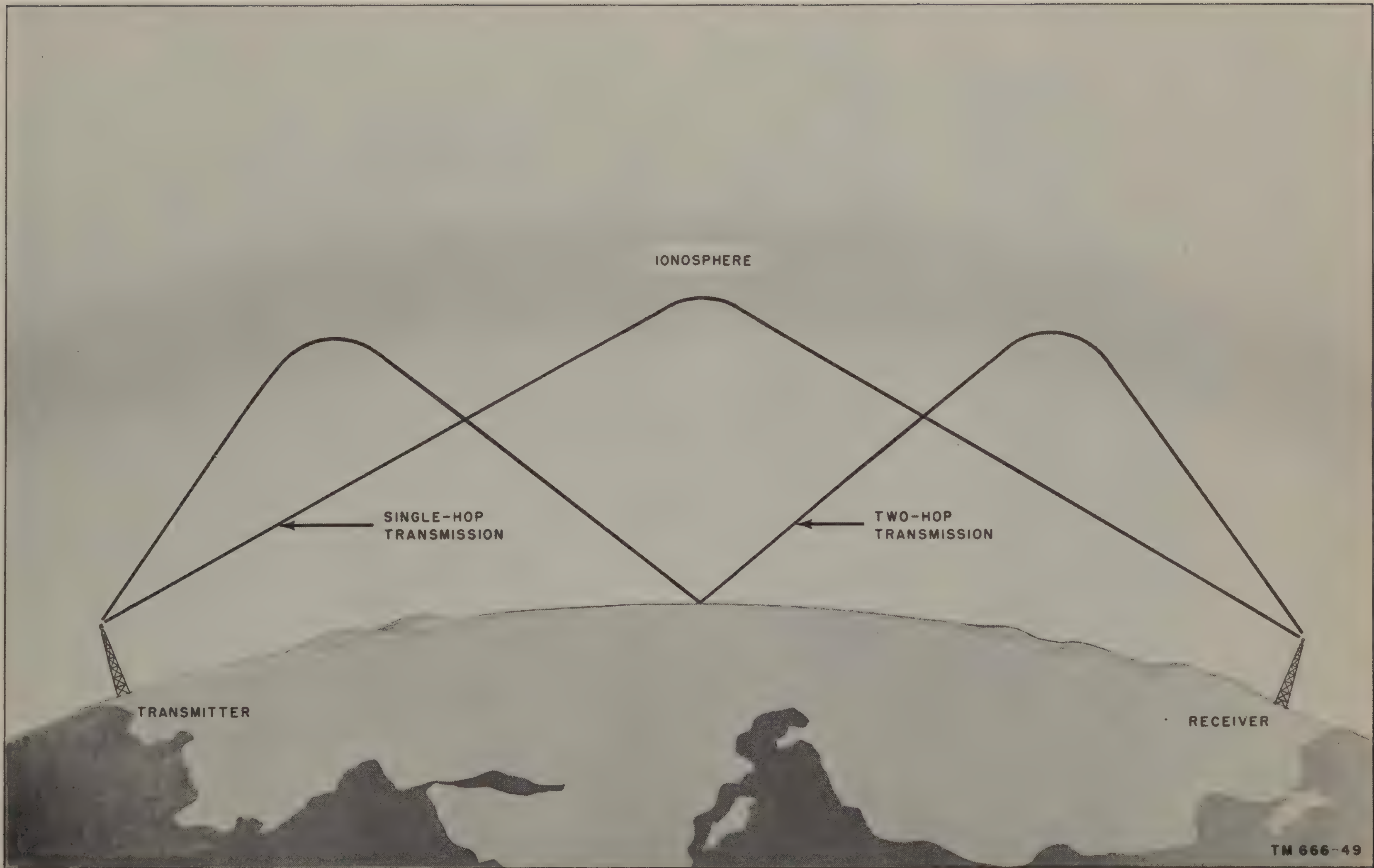


Figure 39. Modes of sky-wave transmission.

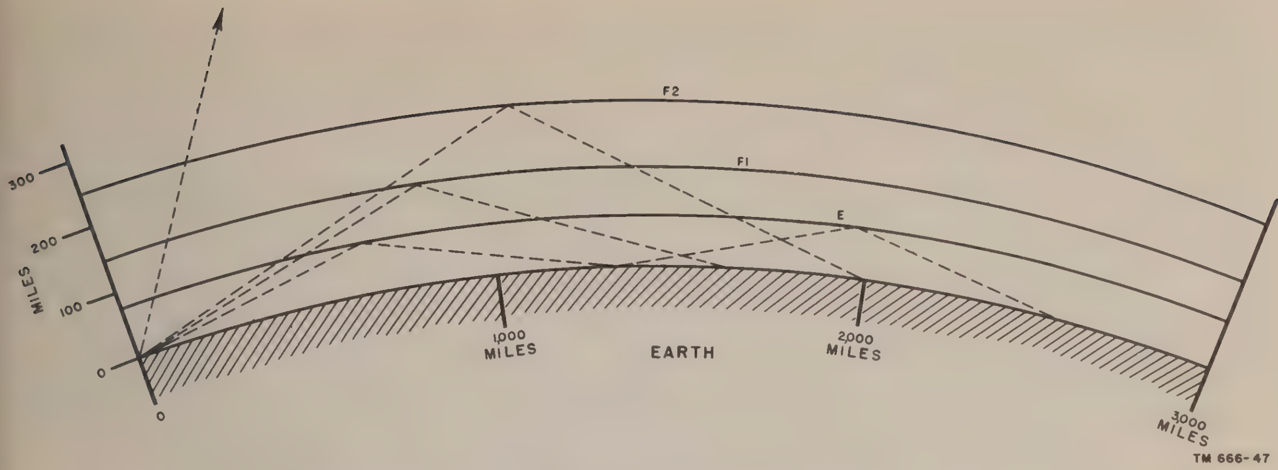


Figure 40. Relating reflected waves to distances along earth's surface.

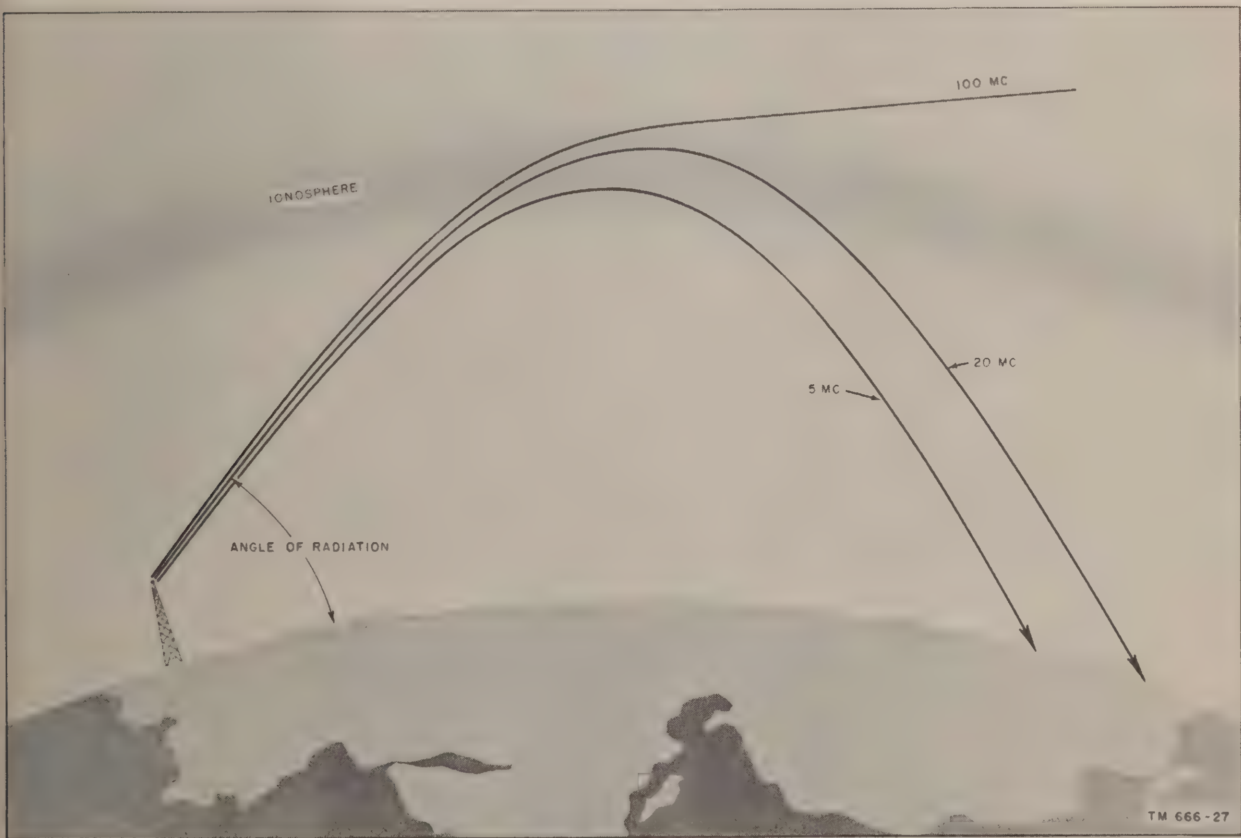


Figure 41. Frequency versus distance for returned waves.

the ionospheric layer and, therefore, does not return to earth. On consideration, it will be seen that these two definitions are the same, since the angle at which the wave first returns and the angle at which it just does not return are the same angle. Also, the critical angle is measured (for purposes of calculation) between the wave path at incidence with the ionosphere and a line extended from the ionosphere to the center of the earth; however, for ease of explanation, the critical angle and all other angles of incidence are taken as angles made by the wave with either the earth or the ionosphere considered as horizontal plane surfaces.

(1) Figure 42 shows a given wave at various angles of incidence with the ionosphere

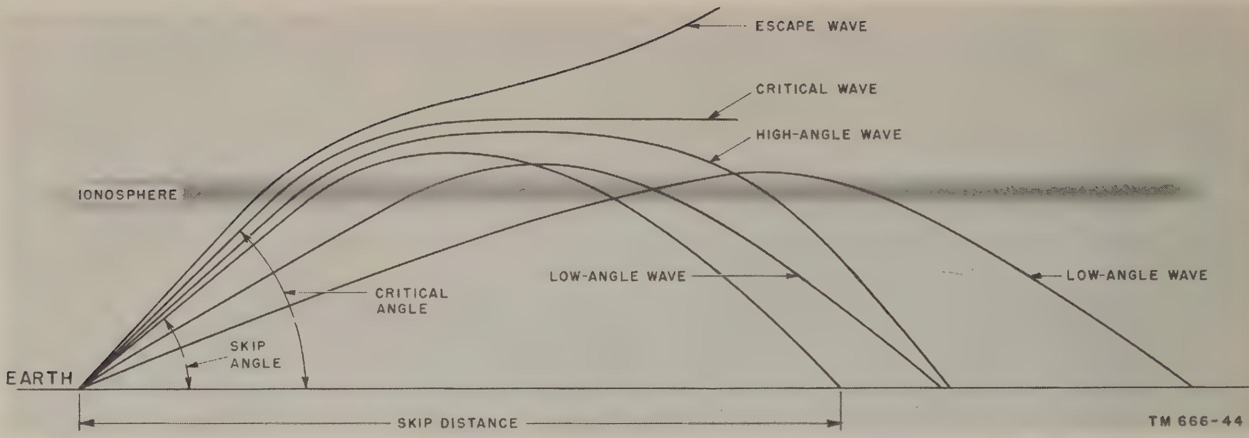


Figure 42. Incident wave paths for a plane earth and a plane ionosphere.

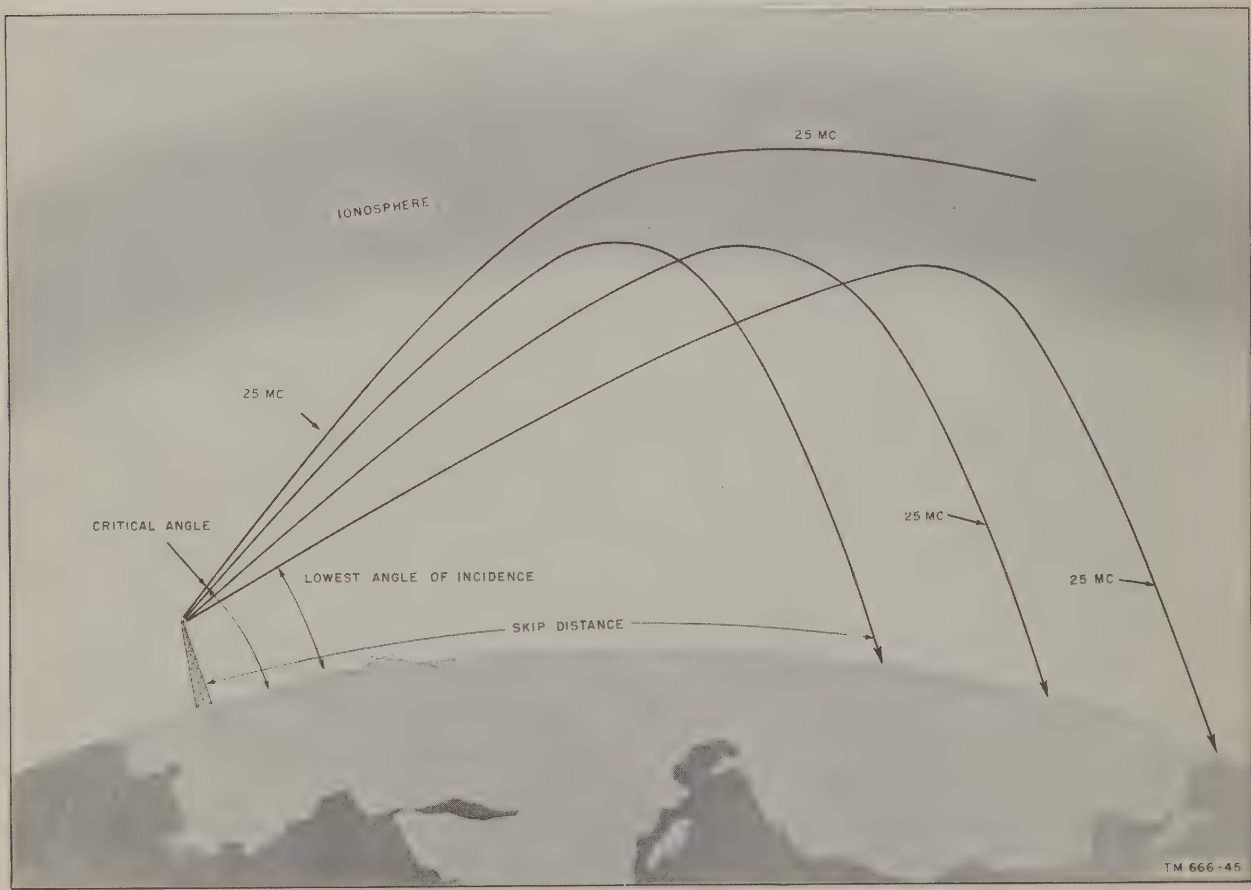


Figure 43. High-frequency wave at various angles of incidence.

and its resultant variation in refraction or reflection. Note that at angles of incidence larger than the critical angle, the wave is not sufficiently refracted in the ionosphere and escapes into space. As the angle of incidence decreases below the critical angle, the wave returns to earth at *decreasing* distances from the transmitter until a point of minimum distance, the skip distance, is reached. Then, as the angle of incidence continues to decrease, the distance between the

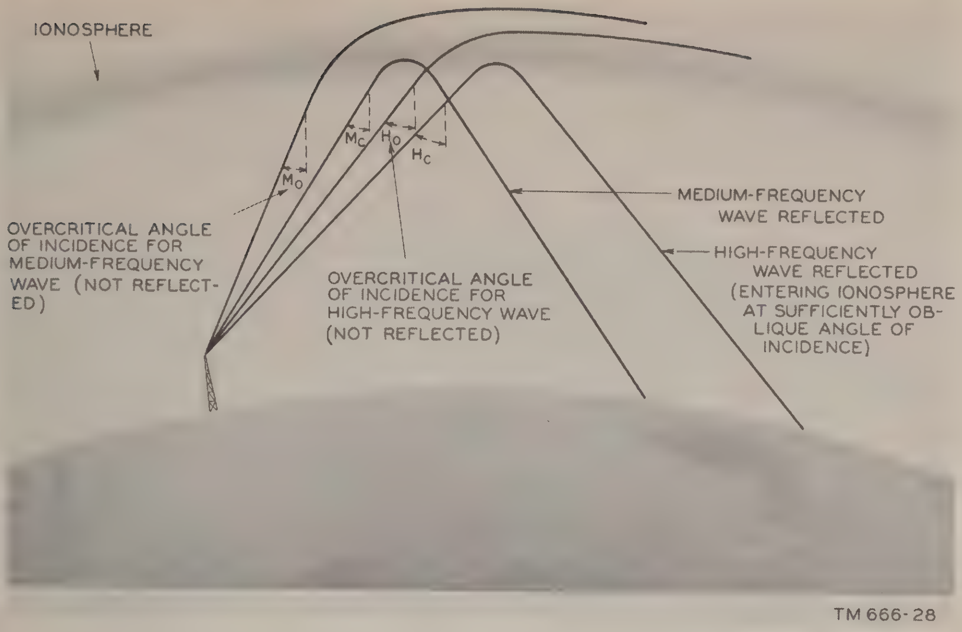


Figure 44. Relation of angle of incidence to usable frequency.

transmitter and the point at which the wave returns *increases* and continues to increase for smaller and smaller angles of incidence. Also, any high-angle wave which returns beyond the skip distance is attenuated greatly, and the skip distance remains as the point at which the wave first is returned in strength to the earth.

(2) This irregular variation of the return distance with regular variation of the incident angle results from the fact that the ionosphere acts principally as a refracting medium for the larger angles of incidence. If the angle of radiation of the transmitted wave can be controlled, the smaller angles of radiation result in greater distance of communication. Figure 43 shows sky waves of a fixed frequency propagated at the critical angle and at various smaller angles. Note that the smaller the angle the greater the distance at which the wave is returned to earth.

(3) The critical angle for a given frequency is not to be confused with the critical frequency for a given layer of the ionosphere. The critical frequency, as explained in paragraph 22, is the highest frequency a given density of ionization will return directly to the earth when propagated at a vertical angle (incident at 90° to the ionosphere). Although a vertically propagated frequency higher than the critical frequency does not return to the earth, it is possible that this same frequency propagated at a different angle will return. In other words, frequencies higher than the critical frequency may be used if the angle of incidence is less than 90°. Figure 44 illustrates this relationship between the angle of incidence and the use of frequencies higher than the critical frequency to obtain communication.

28. Maximum Usable Frequency (MUF)

a. For any given ionized layer of fixed height and ion density, and for a transmitting antenna with a fixed angle of radiation, there is a frequency (higher than any other) that will return to the earth at a given distance. This frequency is the *maximum usable frequency for that distance;* moreover, it is always a frequency higher than the critical frequency because the angle of incidence is less than 90°. Thus, for any given great-circle distance along the earth, there is a maximum usable frequency which is the highest frequency that will be reflected from a given layer of the ionosphere and that will return to the earth at the great circle distance. If the distance between transmitter and receiver increases, the maximum usable fre-

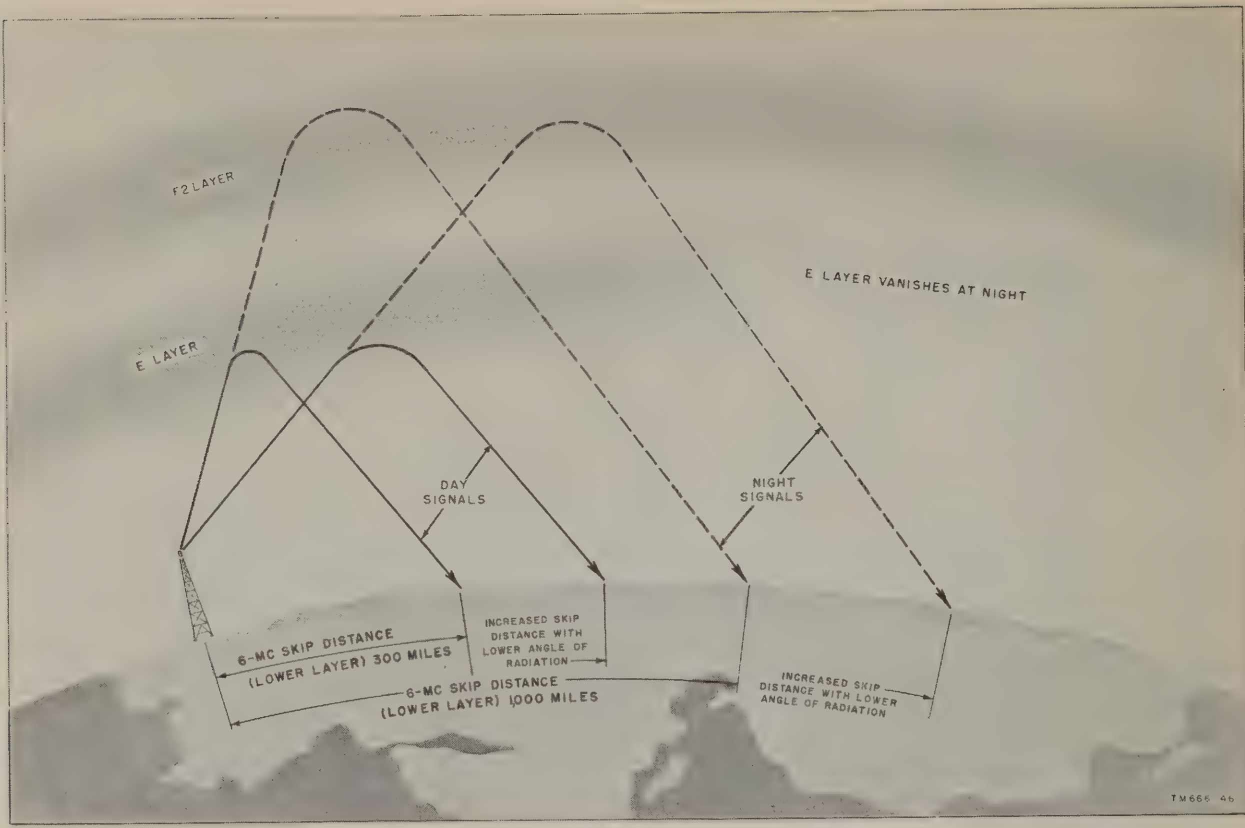


Figure 45. Relationship of distance, time, angle, and frequency.

quency increases. In other words, the greater the transmission distance, the higher the maximum usable frequency.

b. In selecting the proper operating frequency for sky waves which travel along a fixed radio path, the maximum usable frequency is perhaps the most important factor to be considered. If the operating frequency is above the maximum usable frequency, the wave is said to escape, since it then will not be reflected by the ionosphere layer but will pass on through. On the other hand, if the operating frequency is decreased below the maximum usable frequency in the daytime, the wave becomes increasingly attenuated, since, in the high-frequency range, the lower the frequency, the more wave energy is lost through ionospheric absorption. Hence, it is usually desirable for transmission to occur on a frequency as near to the maximum usable frequency as possible. A direct relationship exists between the maximum usable frequency, the condition of the ionosphere, time, and the angle of radiation, as shown in figure 45. Thus, it is possible to predict mean values of maximum usable frequency for propagation over any path for any time in any future month. Since the method of problem solution entails the use of world-contour charts and the use of complicated procedures, it is beyond the scope of this manual, but, as mentioned previously, this information may be obtained by consulting TM 11–499, Radio Propagation, and TB 11–499–( ), the monthly supplement thereto.

c. If the density of the ionosphere is such that the maximum usable frequency is at a frequency near the critical frequency, the wave is excessively retarded in the ionized layer, and, because of the effects of the earth's magnetic field, splits into two components known as the *ordinary wave* and the *extraordinary wave.* These components, shown in figure 46, are usually of different polarization and phase. The critical frequency for the extraordinary wave is higher than that for the ordinary wave, the difference varying with the intensity of the earth's magnetic field, which changes with geographic position. Since the critical frequency for the ordinary wave is lower than that for the extraordinary wave, a layer of given ion density bends the ordinary wave less

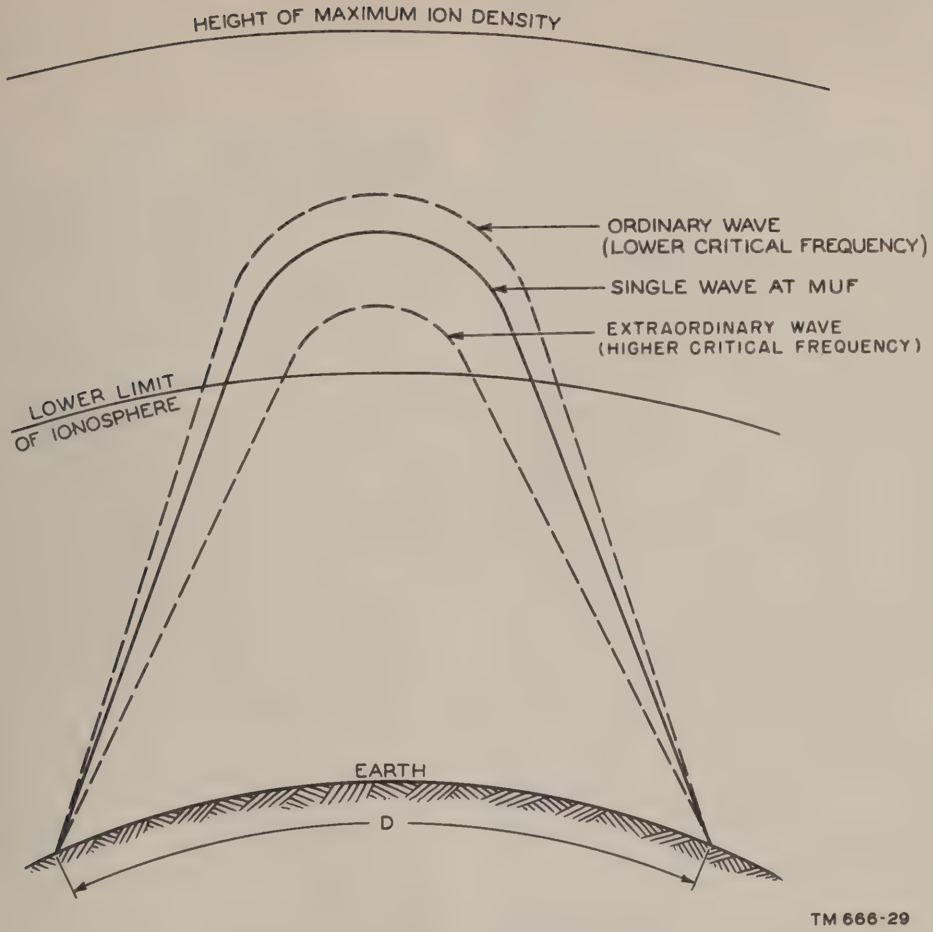


Figure 46. Ordinary and extraordinary waves.

than it does the extraordinary wave. From another point of view, the ordinary wave, which obeys the laws of simple refraction, must penetrate a greater distance into the layer than the extraordinary wave, which responds to both refraction and reflection. Figure 46 shows these two waves in conjunction with the MUF. However, it should be noted that this effect is important only for *F* layer transmission, causing interference fading. The extraordinary wave reflected from the *E* layer is so weak that it does not affect radio reception.

29. Lowest Useful Frequency (LUF)

a. Absorption. The presence of ions in the upper atmosphere not only causes bending and the return to earth of a radio wave of sufficiently low frequency, but also causes part of the wave energy to be absorbed. The collisions of electrons with neighboring molecules of air reduce the intensity of the radio wave below that resulting from the normal spreading of the wave front as it travels out from the transmitter. This absorption process is also of great importance in the practical use of ionospheric radio transmission. During the day, absorption takes place mainly in the *D* region of the ionosphere. Electron densities in this region are considerably less than in the higher regions, but the increased density of the atmosphere itself results in an increase in the number of collisions between electrons and molecules of air, and more than compensates for the scarcity of electrons. During the night, ionization and absorption in the *D* region become negligible. However, there is some absorption for frequencies near the MUF of the *F*2 layer because waves at such frequencies are retarded to such an extent that there is sufficient time for appreciable energy loss to take place in spite of the relatively

small number of collisions. Such absorption is called *deviative* absorption, because it occurs in conjunction with retardation, which causes bending of the waves. Absorption which takes place even though the wave is not appreciably retarded is called *nondeviative* absorption. The absorption in the D region is largely nondeviative.

b. Lowest Useful High Frequency (LUHF). At certain frequencies of transmission, radio waves penetrating into the ionosphere, primarily in the D region and in the lower portion of the E region, lose some of their energy by absorption. Generally speaking, the higher the frequency used, up to the limit of the maximum usable frequency, the less will be the total absorption and the more satisfactory will be the level of communication. Absorption is at a maximum for frequencies of about 500 kc to 2 mc in the daytime, and decreases for both higher and lower frequencies at night. Thus, for frequencies above about 1 mc, the strength of the received sky waves will, in the daytime, increase with frequency (corresponding to decreasing absorption). Finally, a frequency will be reached for any given sky-wave path where the strength of the received signal just overrides the noise level. This frequency is called the LUF. Frequencies lower than the LUF are absorbed to such an extent as to render them too weak for useful communication. It should be noted, however, that the LUF depends on the power of the transmitter as well as on the distance concerned. At night, the noise level increases with decreasing frequency so that, as the frequency is lowered, the signals become weaker with respect to the noise and the LUF eventually is reached. Thus, the term *lowest useful frequency* may apply to either day or night transmission.

c. Summary for Variable Frequency. Assuming constant ionospheric conditions, a constant distance, and single-hop transmission, it can be said that—

(1) Frequencies considerably below the MUF will be attenuated greatly by nondeviative absorption.
(2) Frequencies somewhat below the MUF will be reflected as ordinary and extraordinary waves, either or both of which may be attenuated greatly by deviative absorption.
(3) Frequencies near the MUF will be reflected as ordinary and extraordinary waves, both of fair strength.
(4) Frequencies at the MUF will be received in the greatest possible strength as one wave.
(5) Frequencies above the MUF will escape and not be received, except as *scattered* waves (par. 24).

d. Summary for Variable Distance. Assuming constant ionospheric conditions, a fixed frequency, and single-hop transmission, it can be said that—

(1) At short distances, the wave will skip and not be received, except of course as a ground wave.
(2) At just a certain distance, called the skip distance, the wave will be received as one wave and at its greatest strength.
(3) At a greater distance, the wave still will be received but as an ordinary wave and extraordinary waves, with resultant fading because of random polarization.
(4) At still greater distances, the ordinary and extraordinary waves will be received, but either or both will be attenuated considerably by deviative absorption.
(5) At even greater distances, the wave will be attenuated greatly by both deviative and nondeviative absorption.

Note. An important fact to be borne in mind is that radio waves of fixed radiation angle are receivable at distances greater than the skip distance, but that as this distance is increased appreciably, increased attenuation results.

30. Optimum Working Frequency (FOT)

Variations in the ion density of the ionosphere layers occur from day to day, and from hour to hour. Predictions on which the MUF's are based are made by averaging long-range observations, and do not take into account these day-by-day fluctuations. Therefore, the actual upper limiting frequency must be selected at a value which will insure against the probability of the operating frequency becoming greater than the MUF for any particular day. For the $F2$ layer, the optimum working frequency thus is selected at approximately 85 percent of the MUF for that particular transmission path. The optimum working frequency for the combined E–$F1$ layer may be taken as the MUF, since the day-by-day variations in E layer ionization are small. Of course, if the LUF is nearly equal to the MUF for a given transmission path, the optimum working frequency must be selected at a value consistent with both. During moderate ionospheric storms, communication often can be assured by operating

at frequencies slightly lower than normal, since critical frequencies are usually lower than normal during these periods.

31. Received Signal Strength

a. Factors. Whether the ionosphere will support transmission of sky waves over a given signal path at a certain time may be determined by finding the MUF and LUF for this path. If a consistent optimum working frequency can be derived from these factors, radio communication over this signal path is known to be possible. In the downcoming sky wave, we are not dealing with a steady wave of constant amplitude and phase, but one which may fade suddenly and greatly, whose polarization may be changing constantly, which may be composed of not one but many component waves, which is affected by reflection at the ground near the receiver, and which is subject to the variations in height and energy absorption in the ionosphere, and to focusing by the ionosphere. These difficulties may be minimized by due regard to certain factors upon which the received signal strength depends, such as transmitter power, antenna gain, transmission-path distance, absorption function of the signal path, and interference losses. It is obvious that the transmitter must supply the amount of power required to provide a field of sufficient strength at the receiver.

b. Gain of Antenna. The gain of an antenna depends primarily on its design. The various types of antennas and their characteristics will be discussed in chapter 3, but it may be said here that transmitting antennas are designed for high efficiency in radiating energy, and receiving antennas are designed for the efficient pickup of energy. On many radio circuits, transmission is required between a transmitter and only one receiving station. In such cases, it is desirable to radiate as much energy as possible in the proper direction since radiated energy is useful only in that direction. Directional characteristics in a receiving antenna increase the energy pickup or gain in the favored direction and reduce the reception of unwanted noise and signals from other directions. The general requirements for receiving and transmitting antennas are that they have small energy losses and that they be efficient as receptors and radiators.

c. Field Intensity. In traversing a nonionized region of the atmosphere, practically no energy is lost from the wave, and the only decrease in field intensity is that caused by the spreading out of the wave front, the *inverse distance attenuation.* The field intensity along a path, encountering no obstacles (neither large masses nor ions) and no interfering wave trains, varies inversely as the distance from the emitting source; the energy density in the waves, which is proportional to the square of the field intensity, varies inversely as the square of the distance (the familiar *inverse-square law*). As mentioned previously, the field intensity usually is measured in microvolts per meter.

d. Absorption. The presence of ions in the upper atmosphere not only causes bending and the return to earth of a radio wave of sufficiently low frequency, but also causes part of the wave energy to be dissipated because of the collisions of the electrons with neighboring molecules of air. This reduces the intensity of the radio wave below that resulting from the normal spreading of the wave front as it travels out from the transmitter. This absorption process is of great importance in the practical use of ionospheric radio transmission. During the day, absorption takes place mainly in the *D* region of the ionosphere. Here, electron densities are considerably less than in higher regions, but the increased density of air molecules results in an increase in the number of collisions which more than compensates for the scarcity of electrons. During the night, ionization and absorption in the *D* region become negligible. However, there is still some absorption for frequencies near the MUF of the F_2 layer because waves at such frequencies are retarded, and there is sufficient time for appreciable energy loss to take place in spite of the relatively small number of collisions. As stated before, such absorption is called *deviative absorption* because it occurs in conjunction with retardation, which also causes bending of the waves. Absorption which takes place even when the wave is not appreciably retarded is called *nondeviative absorption.* Absorption in the *D* region is largely nondeviative.

e. Antenna Height. The received signal field is usually a combination of the direct field resulting from the downcoming sky wave, together with that caused by the wave reflected from the ground. The resultant electric vector at the antenna, therefore, is dependent on variations of the ground-reflection coefficient as well as on the instantaneous changes in both the amplitude and direction of the downcoming sky wave. The height of the

receiving antenna and the angle at which the sky wave approaches it may thus be contributing factors to the received signal strength, since polarization and phase of the ground-reflected component may serve either to cancel out, or to contribute to, the resultant field strength at the antenna.

32. Fading

Because of fluctuations in ionospheric conditions, the received intensity of the sky wave is not constant, but varies with time. The term *fading* refers to relatively rapid variations which occur during a space of minutes, seconds, or even fractions of a second. In general, fading is more sudden on high than on low frequencies. A type of fading known as *selective fading* also can cause distortion in radiotelephone signals. In such cases, the fading affects certain frequencies more than others and, therefore, may affect the side bands and the carrier wave differently. Fading, which is usually a nuisance, may be reduced by several methods, such as automatic volume control, suppressed carrier transmission, and diversity reception. Discussion of these methods is beyond the scope of this manual.

a. Types of Fading. The many types of fading fall into four principal classes—(1) interference fading, (2) polarization fading, (3) absorption fading, and (4) skip fading. Most of the rapid fading in the input to a receiver is a combination of the first two types; the other two are responsible for slower changes.

b. Interference Fading. Interference fading is caused by phase interference of two or more waves from the same source arriving at the receiver over slightly different paths. If the paths are of different lengths, and their relative lengths vary for some reason, such as fluctuations in the height of the ionosphere layers, the relative phases of the waves arriving over the different paths vary with time, causing alternate reinforcement and cancelation of the field intensity. Because of irregularities in the ionosphere, one downcoming sky wave is really the summation of a great number of waves of small intensity and of random relative phases, and thus the resultant field intensity can vary over wide limits. The rms (root mean square) value of the fading intensity is equal to the *homogeneous field*, or the steady value of the field that would have existed had the ionosphere not broken the wave up into many components.

c. Polarization Fading. Additional variation in the field intensity affecting the receiving antenna occurs as a result of changes in the state of polarization of the downcoming wave relative to the orientation of the antenna. This variation is called polarization fading. In general, the state of polarization of the downcoming sky wave is changing constantly. This is due mainly to the combination, at random amplitudes and phases, of the two oppositely polarized components, the ordinary and the extraordinary wave. The polarization of the downcoming sky wave is generally elliptical. By elliptical polarization is meant that, as the wave travels along the signal path, the electric and magnetic fields remain at right angles to each other and to the direction of propagation, but rotate about the signal path in more or less corkscrew fashion instead of remaining constantly in either a vertical or a horizontal plane with respect to the path, as does the plane polarized wave. This results in random and constantly changing values of the amplitude and orientation of the electric field with respect to the receiving antenna. The state of polarization of sky waves varies more rapidly the higher the frequency, which accounts in part for the rapid fading on the higher frequencies.

d. Absorption Fading. Absorption fading is caused by short-time variations in the amount of energy lost from the wave because of absorption in the ionosphere. In general, the period of this type of fading is much longer than for the other two types, since the ionospheric absorption usually changes slowly. The sudden ionospheric disturbance is an extreme case of this type of fading, although usually it is classified as an irregular disturbance rather than as fading. Somewhat similar to this type of fading, although not caused in the ionosphere but by reflections and absorption in objects close to the receiver, is the type of fading experienced in receiving a signal while moving along in an automobile. The fading out of the signal when the automobile is passing under a bridge or near a heavy steel structure is caused by absorption of the wave's energy by the structure. Effects of this sort are involved in so-called *dead spots* or places where radio reception is particularly difficult. Also, radiation from wires, fences, and steel structures can cause an interference pattern that is relatively fixed in space, and can be noticed on moving the receiving equipment around. Where there are nearby structures which

can cause these effects, care must be exercised in the selection of the receiving site.

e. Skip Fading. Skip fading is observed at places near the limit of the skip distance, and is caused by the changing angle of refraction. Near sunrise and sunset, when the ionization density of the ionosphere is changing, it may happen that the MUF for a given transmission path fluctuates about the actual operating frequency. When the skip distance moves out past the receiving station (sometimes called *going into the skip*) the received intensity abruptly drops by a factor of 100 or more, and just as abruptly increases again when the skip distance moves in again. This may take place many times before steady conditions for transmission are established.

33. Radio Noise and Required Signal Strength

a. Required Signal Strength. The minimum radio field intensity necessary to allow the satisfactory reception of an intelligible signal of a particular type in the presence of radio noise at the receiving station is called the required signal strength for this type of service. As a propagation factor, the required signal strength is subject to wide variation. It depends on the receiving set; the local noise or *static;* the type of modulation of the radio wave, or, in other words, the type of service; and the grade of service desired—e. g., barely intelligible, high fidelity, and so on. It also varies, with the radio noise, according to the time of day and season.

b. Types of Radio Noise. Radio noise may be defined as interference, the energy of which is not confined to a narrow band of frequencies. Two general types of radio noise may be distinguished—(1) impulse noise, which is interference resulting from a single elementary disturbance, or from an aggregate of elementary disturbances with systematic relative phase; and (2) random, or fluctuation noise, which is the aggregate of a large number of elementary disturbances with random relative phases. A distinction between impulse and random noise is not always easy to make. However, electrical, or man-made, noise caused by the operation of electrical equipment is usually of the impulse type, whereas atmospheric noise, originating in thunderstorms or caused by other atmospheric conditions, ordinarily may be considered to have the bandwidth characteristics of random noise. The best example of random noise is the fluctuation noise originating in the resistance components of impedance elements in the receiver or brought about by the fluctuations of electrons within vacuum tubes. Another example is the noise generated by cosmic rays, which are sufficiently high in frequency to penetrate the atmosphere of the earth. This cosmic noise is noticeable only in receivers capable of detecting these frequencies.

(1) *Atmospheric noise.* At the frequencies under consideration in this manual, atmospheric noise and precipitation noise are the most important types to be considered. Radio noise from electrical apparatus, such as the ignition systems of automobiles, may be very serious, but is, more or less, under the control of the observer, and can be largely eliminated if necessary. Atmospheric or precipitation noise, on the other hand, since it originates in thunderstorms, or in rain, snow, or dust storms, usually cannot be eliminated and thus sets the limit for radio reception. Most atmospheric noise is considered to originate in the lightning flashes associated with thunderstorms. Generally, thunderstorms occur much more frequently over the land than over the sea and are more common at low than at high altitudes.

(2) *Cosmic and solar radio noise.* Between frequencies of about 10 and 100 mc, cosmic radio noise originating in interstellar space is known to be the principal source of interference to reception under many circumstances. As stated above, cosmic noise has about the same characteristics as the fluctuation noise originating in components of a receiving set. The sources of cosmic noise are not distributed evenly over the sky but tend to be concentrated in several regions of the celestial sphere, the principal of these regions being near the center of the Milky Way. Consequently, when received on a directional antenna, the noise varies in characteristic manner from hour to hour and from day to day. The reason for the existence of cosmic noise is not well known. Some investigators believe it to be radio-frequency radiation from eruptions, similar to the spot eruptions on our sun, occurring on all the stars in the galaxy; others have

considered it as originating in electron activity in the space between the stars. Recently, it has been found that the sun also acts as a radiator of radio noise at frequencies from about 200 mc up. Except at the time of large sunspot eruptions, solar noise is important only on very high frequencies and when highly directional antennas actually are pointed at the sun; therefore, it need not be considered in relation to practical problems of propagation.

(3) *Receiving set noise.* Noise generated internally in a receiving set is caused by the random motion of electrons in resistance components of impedance elements and in the fluctuations of the electrons in vacuum tubes. In the absence of all external noise, signals, to be intelligible, must be strong enough to override this internal noise. With only internal noise present, the ability of a receiver to receive a signal usually is expressed as the noise figure of the receiver. Experimental determination of the receiver input terminal voltage required to override the internal noise in typical Army communications receivers shows a value of approximately 2 microvolts for 90 percent intelligibility of 100 percent modulated radiotelephony. Though this value is somewhat dependent on frequency, it is considered sufficiently accurate for all frequencies between 1.5 and 20 mc.

c. Noise Figure. For many years, radio engineers were faced with the problem of devising a system for rating a receiver or an amplifier on its merits from the standpoint of low noise. The problem was complicated by the fact that in addition to the useful output voltage of a generator (the generator, under operating conditions, being an antenna and the useful output voltage being the desired signal voltage) a certain noise voltage is always present. In an antenna, this noise voltage would include that caused by thermal resistor noise, and atmospheric and cosmic noise; in a standard voltage generator, this voltage would include only that resulting from thermal resistor noise. Because of the fluctuations of atmospheric- and cosmic-noise voltages with time, location, and construction and orientation of the antenna, these noise voltages do not offer a constant standard for rating a receiver or an amplifier. However, thermal noise, presenting a readily computed voltage offers a satisfactory standard against which the noise introduced by a receiver or an amplifier can be rated. Based on this principle, a system of rating a receiver in terms of its noise figure has been devised for this purpose.

(1) In a receiving system, the total noise is the sum of the tube noise, the thermal noise in the input circuit, the thermal noise in the output circuit, and the antenna noise. Antenna noise is the induced atmospheric and cosmic noise appearing at the receiver input.

(2) The signal-to-noise ratio of an ideal receiving system can be expressed as

$$\begin{matrix}\text{Signal-to-noise power}\\ \text{ratio of ideal system}\end{matrix} = \frac{\text{available signal power}}{\text{ideal available noise power}}$$

where the *ideal available noise power* is the power developed across the antenna resistance by the thermal noise voltage. The available signal power at the receiver input is the power that the signal will develop across an input resistance equivalent to the antenna resistance. Noise figures usually are expressed in terms of power ratios or in *db*.

(3) The noise figure of an actual receiver is obtained from the following ratio:

$$\text{Noise figure} = \frac{\text{signal-to-noise power ratio for an ideal receiver}}{\text{signal-to-noise power ratio of an actual receiver}}$$

(4) The required signal power at the input of an actual receiver is the required signal power for an ideal receiver multiplied by the receiver noise figure for the same signal-to-noise ratio.

d. Types of Modulation and Service Gain. Other factors upon which the required signal strength of a receiving system depends are known as *type of modulation* and *type of service* gain. Higher signal-to-noise ratios are required in commercial high-quality broadcast work than in many other types of service. On the other hand, in general code systems, such as automatic high-speed telegraphy or teletypewriter systems, the output signal-to-noise ratio need not be large, since the mechanism operates when the signal exceeds the noise by only

a small margin. The gain required for a certain type of service is the relative signal strength required for that type of communication as compared with the signal required for a reference type. This reference type of service corresponds to 90 percent intelligibility of speech and is comparable to the grade of service known as *order wire* in telephonic communications.

Section IV. SUMMARY AND REVIEW QUESTIONS

34. Summary

a. Ground-wave propagation refers to those types of radio transmission which do not make use of ionospheric reflections.

b. The direct-wave component travels directly from the transmitting to the receiving antenna.

c. The ground-reflected component undergoes a phase reversal of 180° upon reflection from the ground.

d. This phase reversal may cause serious signal-voltage cancelation between the ground-reflected and the direct-wave components.

e. The surface-wave component is affected primarily by the conductivity and dielectric constant of the earth.

f. The surface-wave component is essentially vertically polarized at appreciable distances from the antenna.

g. The tropospheric-wave component is refracted in the lower atmosphere by sharp changes in density and humidity of the air.

h. One of the common causes of tropospheric refraction is temperature inversion.

i. *Trapped waves* may follow the curvature of the earth for distances far beyond the optical horizon of the transmitter.

j. The frequency characteristics of the ground wave determine what particular component will prevail along any given signal path.

k. For frequencies above 30 mc, the distance range of the ground wave can be increased by increasing the antenna height as well as by increasing the radiation power.

l. The ionosphere is composed of one or more electrically conducting layers which bend radio waves back toward the earth.

m. The ionosphere layers are formed by ionization of the gas molecules composing them.

n. Recombination goes on constantly, so that an ionized layer does not necessarily last indefinitely.

o. The chief cause of ionization of the ionosphere is ultraviolet radiation from the sun.

p. Sunspots have the effect of increasing the ionization of ionized layers.

q. Ionization occurs in different layers, depending on the frequency of the ultraviolet radiation causing it, and on the critical density of the atmosphere.

r. Although the number of layers is subject to variation from time to time, there are usually four distinct layers during the daytime.

s. During the nighttime, only one ionized layer—the *F* layer—usually exists.

t. The *D* region is the lowest layer, and it is chiefly important for its absorption effects.

u. The *E* layer is important for reflection of radio waves up to about 20 mc.

v. For transmission above 20 mc, the *F*, *F*1, and *F*2 layers are most important.

w. The virtual height, or apparent height, of an ionized layer is considerably greater than the actual layer height.

x. The chief factor that controls long-distance communication is the ionization density of the ionized layer.

y. The higher the frequency of transmission, the greater must be the density of ionization to reflect waves back to earth.

z. The critical frequency is the highest frequency at which waves sent vertically upward are reflected directly back to earth.

aa. The upper layers are the most highly ionized and, therefore, they reflect the higher frequencies.

ab. Waves of all frequencies higher than the critical frequency are not reflected back to earth, but are said to escape.

ac. Changes in the sun's state of activity which cause variations in the amount of its radiation will result in variations in the conformation of the ionosphere.

ad. Regular variations can be predicted, and fall into four classes: diurnal, seasonal, 11-year, and 27-day.

ae. Diurnal variation is caused by the rotation of the earth and results in higher intensities of ionization during the daytime.

af. Seasonal variation causes shifts in the maximum ion density in the *D*, *E*, and *F* layers, being greater in summer than in winter.

ag. The ion density of the *F*2 layer, however, is much greater in winter than in summer.

ah. The 11-year variation is caused by the cycle of sunspot activity which rises to a maximum approximately every 11 years and decreases to a minimum in the intervening years.

ai. At times of sunspot maxima, higher frequencies may be used generally for communications over long distances.

aj. The 27-day variation results from the rotation of the sun about its axis.

ak. The sporadic *E* is an ionized cloud which appears at indefinite intervals and at a slightly higher level than the normal *E* layer.

al. Sudden ionospheric disturbances are the cause of sudden radio fadeouts.

am. During ionospheric storms, there are large variations from normal of critical frequencies, layer heights, and absorption.

an. Scattered reflections may cause signal distortion and so-called *flutter fading*.

ao. Sky-wave transmission is possible because of reflections from ionosphere layers.

ap. The skip distance is the shortest distance from the transmitter at which radio waves of a given frequency will be reflected back to earth.

aq. The skip zone depends upon the extent of ground-wave range and disappears entirely if the ground-wave range equals or exceeds the skip distance.

ar. Signal paths involving one and two reflections from the ionosphere are called, respectively, *single- and double-hop modes of transmission*.

as. Paths which radio waves normally traverse in traveling from transmitter to receiver are usually directly above great-circle paths.

at. The MUF is the highest sky-wave frequency that is usable for a particular radio circuit at a particular time.

au. The greater the transmission distance, the higher may be the MUF.

av. The chief effect of the extraordinary wave on communications is to cause severe interference fading.

aw. The LUF is the lower limiting frequency for satisfactory sky-wave communication for a radio circuit at a particular time.

ax. The LUF is determined by the strength of the sky-wave signal in relation to that required to overcome noise.

ay. The sky-wave field intensity is equal to the required field intensity at the LUF.

az. For the *F*2 layer, the optimum working frequency usually is selected at approximately 85 percent of the MUF for the particular signal path.

ba. The received signal strength depends upon such factors as transmitter power, antenna gain, transmission path distance, absorption function, and interference losses.

bb. The gain of an antenna depends primarily upon its design.

bc. The general requirements for receiving and transmitting antennas are that they have small energy losses and are efficient receptors or radiators.

bd. The free-space electric field intensity is inversely proportional to the distance from the transmitter.

be. Absorption that takes place even when the wave is not appreciably retarded in the ionosphere is called *nondeviative absorption*.

bf. Deviative absorption occurs in conjunction with retardation which also causes bending of the waves.

bg. The height of the antenna and the angle at which the sky wave approaches it may be contributing factors to the received signal strength.

bh. Phase interference of two or more waves from the same source arriving at the receiver by different paths is called *interference fading*.

bi. Changes in the state of polarization of downcoming sky waves relative to the orientation of the antenna is called *polarization fading*.

bj. Absorption fading is caused by short-time variations is the amount of energy lost from the wave absorption in the ionosphere.

bk. Skip fading is caused by waves alternately escaping and returning to earth.

bl. The required field strength is the minimum radio field intensity necessary to the satisfactory reception of an intelligible signal.

bm. Radio noise may be classified as impulse noise, and random, or fluctuation, noise.

bn. Most atmospheric noise is considered to originate in lightning flashes associated with thunderstorms.

bo. Cosmic noise originates in outer space and usually affects reception at frequencies of from 10 to 100 mc.

bp. Receiving set noise is caused by the random fluctuations of electrons in resistance components and in vacuum tubes.

bq. Radio receivers may be rated according to their *noise figure*.

br. The noise figure is equal to the ratio between

the signal-to-noise ratio for an ideal receiver and that for an actual receiver.

bs. Different types of service require different values of signal-to-noise ratio for satisfactory operation.

35. Review Questions

a. What are the factors affecting ground-wave propagation?

b. What are the separate components of the ground wave?

c. What happens to the ground-reflected component upon reflection from the earth's surface?

d. What may be done to reduce the signal-voltage cancelation caused by the ground-reflected component arriving at the receiver out of phase with the direct-wave component?

e. What affects the surface-wave component?

f. What is meant by temperature inversion?

g. What is the normal range of frequency for ground waves?

h. Describe *trapped waves*.

i. How are the ionosphere layers formed?

j. What is meant by ionization? By recombination?

k. What is the principal cause of ionization?

l. What effects do sunspots have on the ion layers?

m. What is meant by *Dellinger fade?*

n. Name the ionosphere layers and their relative heights.

o. What general effect does the D region have on hf waves?

p. What happens to the various layers during the night?

q. Are the ionosphere layers limited to any given number?

r. How does refraction take place in the ionosphere?

s. Describe *virtual height*.

t. Define *critical frequency*.

u. Briefly describe the regular variations of the ionosphere.

v. What is *sporadic E?*

w. What usually happens to radio communications during severe ionospheric storms?

x. What are *scattered reflections*?

y. Give the factors affecting sky-wave propagation.

z. What is the skip zone?

aa. What is the difference between the skip zone and the skip distance?

ab. Describe single- and double-hop radio paths.

ac. What is meant by *short-path* and *long-path* transmission?

ad. Define maximum usable frequency.

ae. How does variation in the oblique angle of incidence affect the MUF?

af. How does the extraordinary wave affect communications?

ag. What happens to waves of frequencies greater than the MUF?

ah. What is meant by the lowest usable high frequency?

ai. What happens to waves of frequencies lower than the LUF?

aj. What optimum working frequency usually is selected for $F2$ layer propagation?

ak. What is *received signal strength*?

al. What are the general requirements for receiving and transmitting antennas?

am. What is the cause of absorption?

an. How does the height of the receiving antenna affect reception?

ao. What is meant by *interference fading*? By *polarization fading*?

ap. When does skip fading usually occur?

aq. Upon what factors does *required signal strength* depend?

ar. What is the cause of atmospheric noise? Cosmic noise? Receiving set noise?

as. What is the noise figure of a radio set?

at. How does the type of service affect the required signal-to-noise ratio?

CHAPTER 3

HALF-WAVE AND QUARTER-WAVE ANTENNAS

Section I. BASIC THEORY

36. Introduction

The electric and magnetic fields radiated from an antenna form the electromagnetic field, and this field is responsible for the transmission and reception of electromagnetic energy through free space. An antenna, however, is also part of the electrical circuit of a transmitter or a receiver and, because of its distributed constants, it acts as a circuit containing inductance, capacitance, and resistance. Therefore, it can be expected to display definite voltage and current relationships in respect to a given input. A current through it produces a magnetic field, and a charge on it produces an electric field. These two fields taken together form the induction field. To gain a better understanding of antenna theory, a review of the basic electrical concepts of voltage and electric field, and current and magnetic field is necessary.

37. Voltage and Electric Field

a. Electric Field.

(1) When a capacitor is connected across a source of voltage, such as a battery (fig. 47), it is charged some amount, depending on the voltage and the value of capacitance. Because of the emf (electromotive force) of the battery, negative charges flow to the lower plate, leaving the upper plate positively charged. Accompanying the accumulation of charge is the building up of the electric field. The flux lines are directed from the positive to the negative charges and at right angles to the plates.

(2) If the two plates of the capacitor are spread farther apart, the electric field must curve to meet the plates at right angles (fig. 48). The straight lines in A become arcs in B, and approximately semicircles in C, where the plates are in a straight line. Instead of flat metal plates, as in the capacitor, the two elements can take the form of metal rods or wires. The three-dimensional view in figure 49 depicts the electric field more accurately. In A of figure 49 the wires are approximately 30° apart, and the flux lines are projected radially from the positively charged wire to the negatively charged wire. In B of figure 49 the two wires lie in a straight line, and the flux

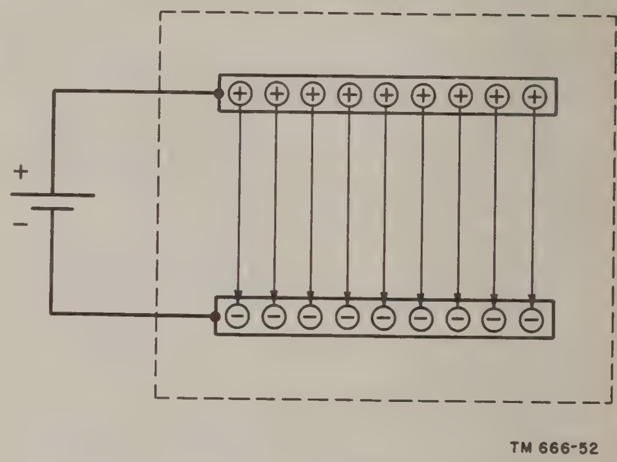


Figure 47. Charges on plates of a capacitor.

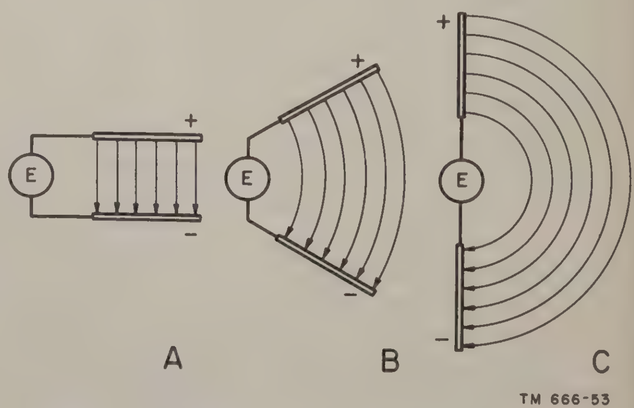


Figure 48. Electric field between plates at various angles.

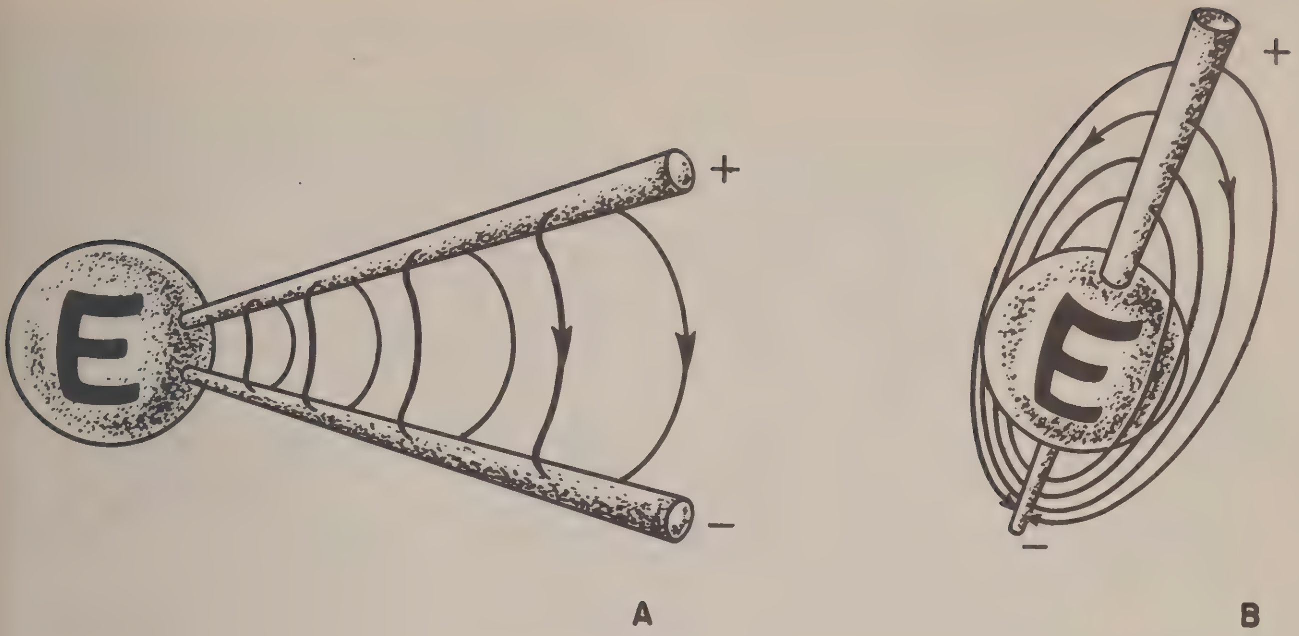


Figure 49. Electric field between wires at various angles.

lines form a pattern similar to the lines of longitude around the earth. To bring out the picture more clearly, only the lines in one plane are given.

b. Voltage.

(1) Assume that the sphere marked *E* in *B* of figure 49, is a transmitter supplying r-f energy. The two wires then can serve as the antenna for the transmitter. R-f energy is radiated from the antenna and charges move back and forth along the wires, alternately compressing and expanding the flux lines of the electric field. The reversals in polarity of the transmitter signal also reverse the direction of the electric field.

(2) When a charge is put on the plates of a capacitor by means of a battery, an electric field is set up between its plates. The flow of charge from source to capacitor ceases when the capacitor is fully charged, and the capacitor is said to be charged to a *voltage* equal and opposite to that of the source. The charged capacitor can be used as a source of emf since it stores energy in the form of an electric field. This is the same as saying that *an electric field indicates voltage*. The presence of an electric field about an antenna also indicates voltage. Since the polarity and the amount of charge depend on the nature of the transmitter output, the antenna voltage also depends on the energy source. For example, if a battery constitutes the source, the antenna charges to a voltage equal and opposite to that of the battery. If r-f energy is supplied to a half-wave antenna, the voltage across the antenna lags the current by 90°. The half-wave antenna acts as if it were a capacitor, and it can be described as capacitive.

38. Current and Magnetic Field

a. Current. A *moving* charge along a conductor constitutes a current and produces a magnetic field around the conductor. Therefore, the flow of charge along an antenna also will be accompanied by a magnetic field. The intensity of this field is directly proportional to the flow of charge. When the antenna is uncharged, the current flow is maximum, since there is no opposing electric field. Because of this current flow, a charge accumulates on the antenna, and an electric field builds up in increasing opposition to the emf of the source. The current flow decreases and when

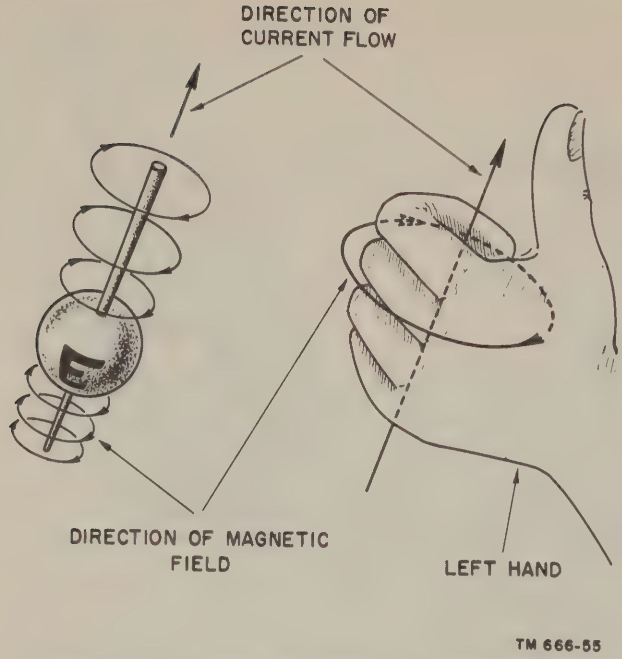


Figure 50. Magnetic field about a half-wave antenna.

the antenna is fully charged, the current no longer flows.

b. Magnetic Field. The magnetic field in the space about a current-carrying device has a specific configuration, with the magnetic flux lines drawn according to a definite rule (fig. 50). Whereas, in the electric field, the electric lines are drawn from a positive charge to a negative charge, in the magnetic field, the flux lines are drawn according to the *left-hand rule.* The direction of current flow is upward along both halves of the antenna. The lines of magnetic flux form concentric loops which are perpendicular to the direction of current flow. The arrowheads on the loops indicate the direction of the field. If the thumb of the left hand is extended in the direction of current flow and the fingers clenched, then the rough circles formed by the fingers indicate the direction of the magnetic field. This is the left-hand rule, or convention, which is used to determine the direction of the magnetic field.

39. Combined Electric and Magnetic Fields

a. When r-f energy from a transmitter is supplied to an antenna, the effects of charge, voltage, current, and the electric and magnetic fields are taking place simultaneously. These effects (fig. 51) have definite time and space relationships to each other. If a half-wave

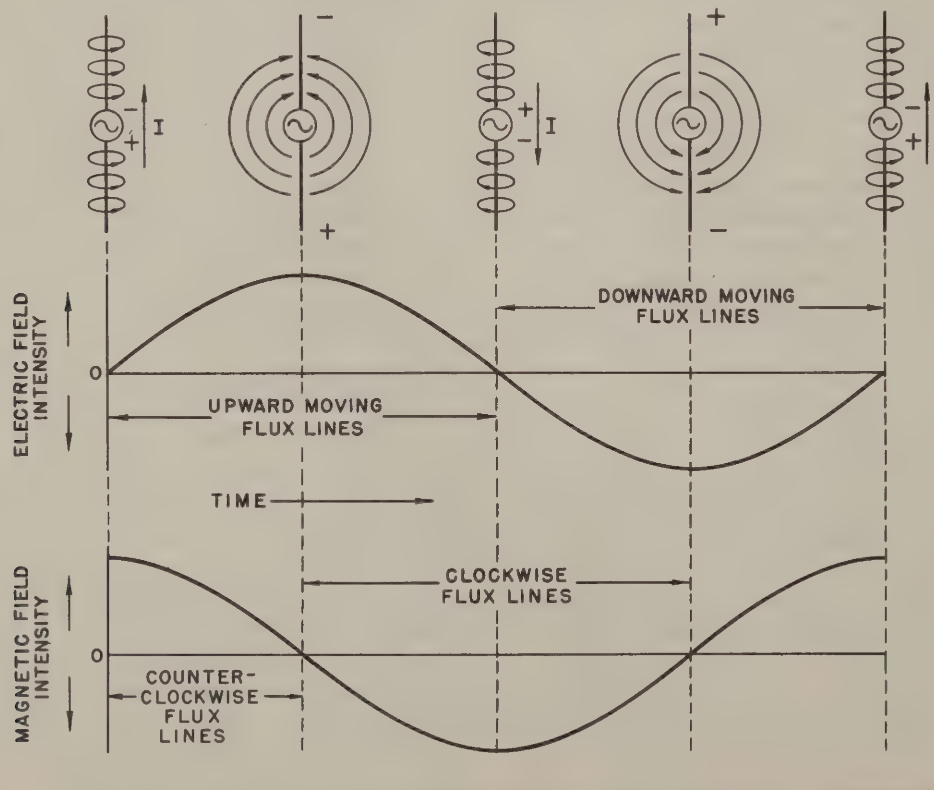


Figure 51. Electric and magnetic fields 90° out of phase.

antenna is used, the relations between charge and current flow can be predicted because of the capacitive nature of this antenna. The voltage will lag the current by 90° and the electric and magnetic fields will be 90° out of phase. With no electric field present (no charge), the current flow is unimpeded, and the magnetic field is maximum. As charge accumulates on the antenna, the electric field builds up in opposition to current flow and the magnetic field decreases in intensity. When the electric field reaches its maximum strength, the magnetic field has decayed to zero.

b. A reversal in polarity of the source reverses the direction of current flow as well as the polarity of the magnetic field, and the electric field aids the flow of current by discharging. The magnetic field builds up to a maximum, and the electric field disappears as the charge is dissipated. The following half-cycle is a repetition of the first half-cycle, but in the reverse direction. This process continues as long as energy is supplied to the antenna. The fluctuating electric and magnetic fields combine to form the induction field, in which the electric and magnetic flux maximum intensities occur 90° apart in time, or in *time quadrature*. Physically, they occur at right angles to each other, or in *space quadrature*. To sum up, the electric and magnetic fields about the antenna are in space and time quadrature.

40. Standing Waves

a. The Infinitely Long Conductor. Assume that it is possible to have a wire conductor with one end extending infinitely, with an r-f transmitter connected to this wire. When the transmitter is turned on, an r-f current in the form of sine waves of r-f energy moves down the wire. These waves of energy are called *traveling waves*. The resistance of the conductor gradually diminishes the amplitude of the waves, but they continue to travel so long as the line does not come to an end.

b. The Finite Conductor (Antenna). The antenna, however, has some finite length. Therefore, the traveling waves are halted when they reach the end of the conductor. Assume that

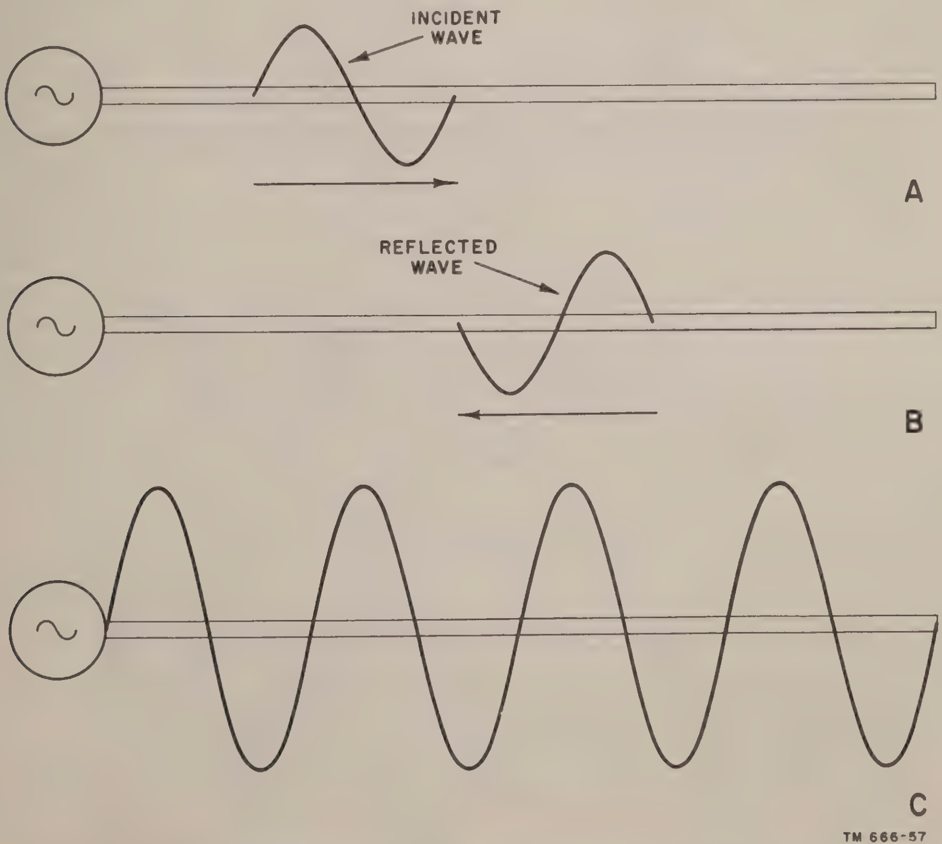


Figure 52. Traveling waves on an antenna and typical resultant wave.

the r-f transmitter is turned on just long enough to allow one sine wave of energy to get on the line (*A* of fig. 52). This traveling wave is moving down the antenna toward the end. When this wave reaches the end of the conductor, the current path is broken abruptly. With the stoppage of current flow, the magnetic field collapses. A voltage is induced at the end of the conductor that causes current to flow *back toward the source*, as in *B* of figure 52. The wave is reflected back to the source, and, if a continual succession of waves is sent down the line, they will be reflected in the same continual pattern. The wave moving from the transmitter toward the end is called the *incident* wave, and its reflection is called the *reflected* wave.

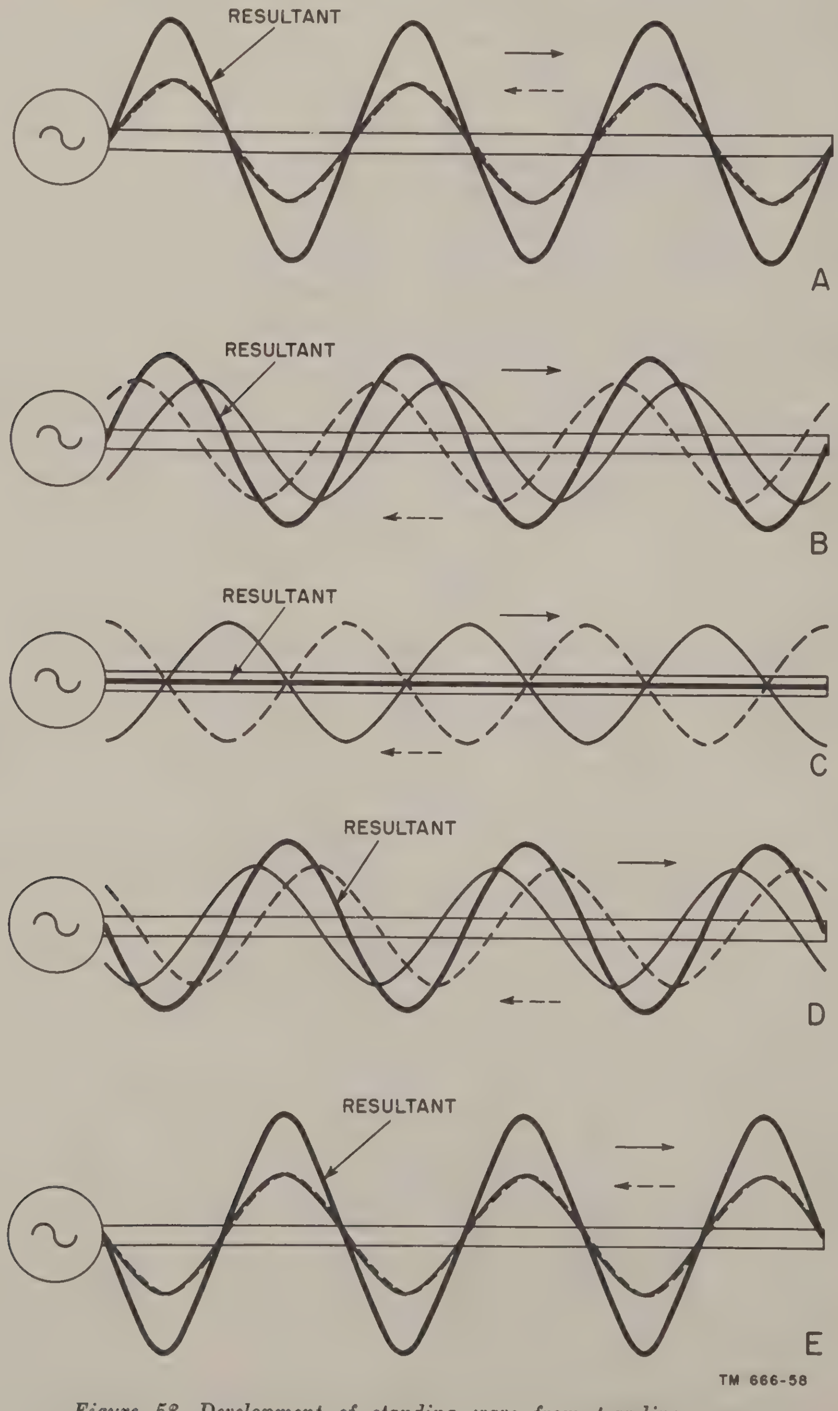


Figure 53. Development of standing wave from traveling waves.

c. Standing Waves.

(1) A continuous flow of incident waves results in a continuous flow of reflected waves. Since there is only one conductor, the two waves must pass each other. Electrically, the only current that actually flows is the *resultant* of both of these waves. The waves can reinforce or cancel each other as they move. When they reinforce, the resultant wave is maximum; when they cancel, the resultant wave is minimum. In a conductor which has a finite length, such as an antenna, the points at which the maxima and minima of the resultant wave occur (*C* of fig. 52) are *stationary*. In other words, the maximum and minimum points stand still, although both the incident and reflected waves are moving. The resultant wave stands still on the line, only its amplitude being subject to change. Because of this effect, the resultant is referred to as a *standing wave*.

(2) The development of the standing wave on an antenna by actual addition of the traveling waves is illustrated in figure 53. At the instant pictured in *A*, the incident and reflected waves just coincide. The result is a standing wave having twice the amplitude of either traveling wave. In *B*, the waves move apart in opposite directions, and the amplitude of the resultant decreases, but the points of maximum and minimum do not move. When the traveling waves have moved to a position of 180° phase difference, the resultant is zero along the entire length of the antenna, as shown in *C*. At this instant there can be no current flow in the antenna. The continuing movement of the traveling waves, shown in *D*, builds up a resultant in a direction opposite to that in *A*. The in-phase condition of the traveling waves results in a standing wave, in *E*, equal in amplitude, but 180° out of phase with the standing wave in *A*.

(3) If the progressive pictures of the standing wave are assembled on one set of axes, the result is as in figure 54. The net effect of the incident and reflected waves is apparent. The curves are lettered with reference to figure 53. As the traveling waves move past each other, the standing wave changes only its amplitude. The fixed minimum points are called *nodes*, and the curves representing the amplitude are called *loops*.

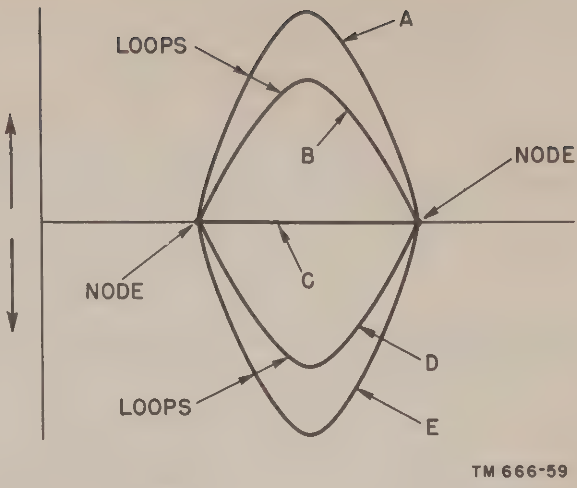


Figure 54. Standing waves.

(4) The concept of the standing wave can be applied to the half-wave antenna with reference to either current or voltage distribution at any instant. This application is possible because there are traveling waves of both voltage and current. Since voltage and current are out of phase on the half-wave antenna, the standing waves also are found to be out of phase.

41. Voltage and Current Distribution on Half-Wave Antenna

a. Instantaneous Voltage and Current.

(1) When an r-f transmitter is feeding a half-wave antenna, positive and negative charges move back and forth along the antenna (figs. 55 and 56). The first picture shows the position of the charges at some arbitrary time, T0. The r-f charges being observed are at the ends of the antenna, and there is a maximum difference in potential between the ends, *A* and *B*. The remaining illustrations show the instantaneous positions of the charges at regular intervals of 22.5° throughout a complete cycle.

(2) To the right of each instantaneous position of the charges are curves representing

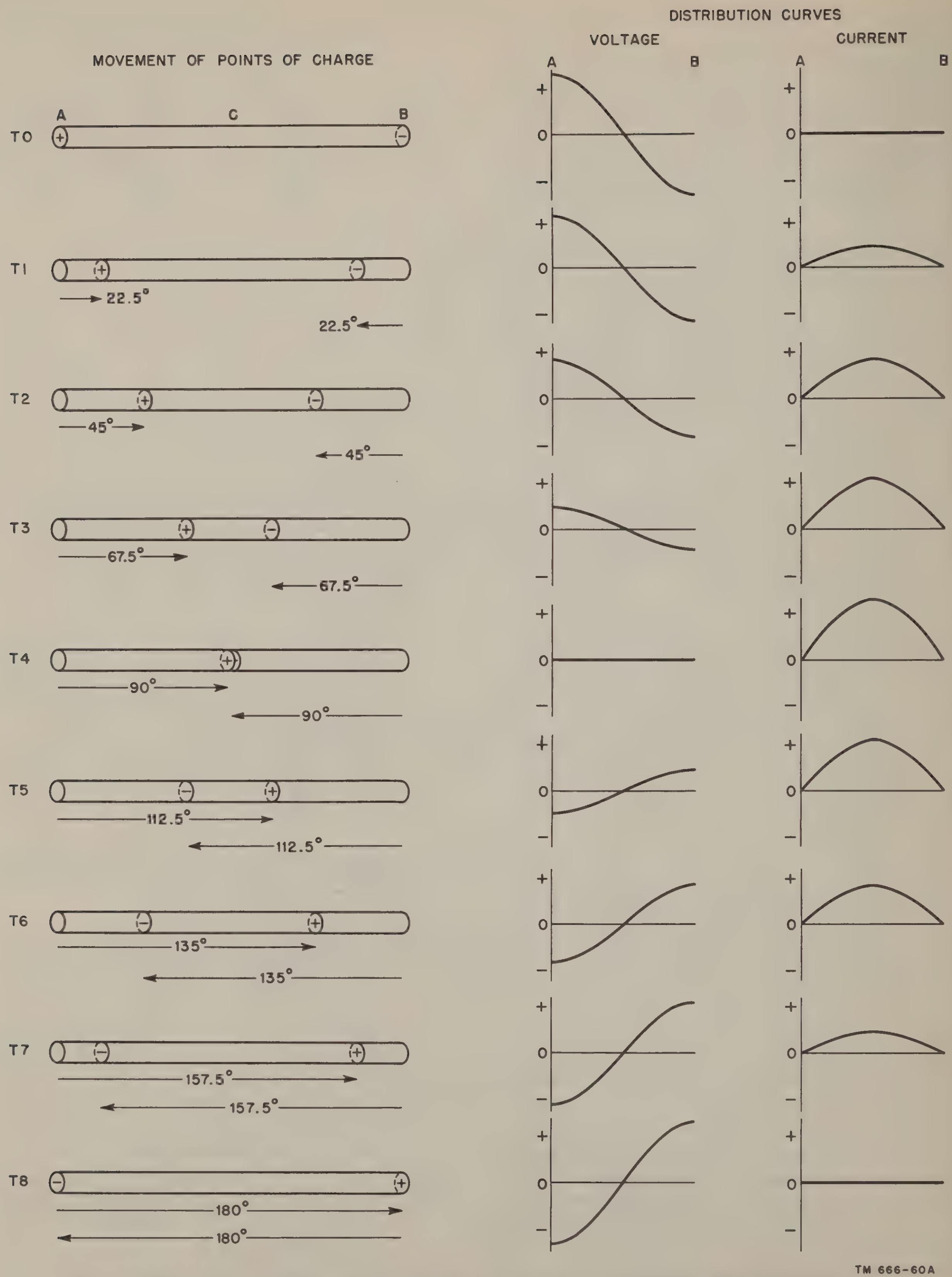


Figure 55. Voltage and current distribution in terms of positive and negative charges.

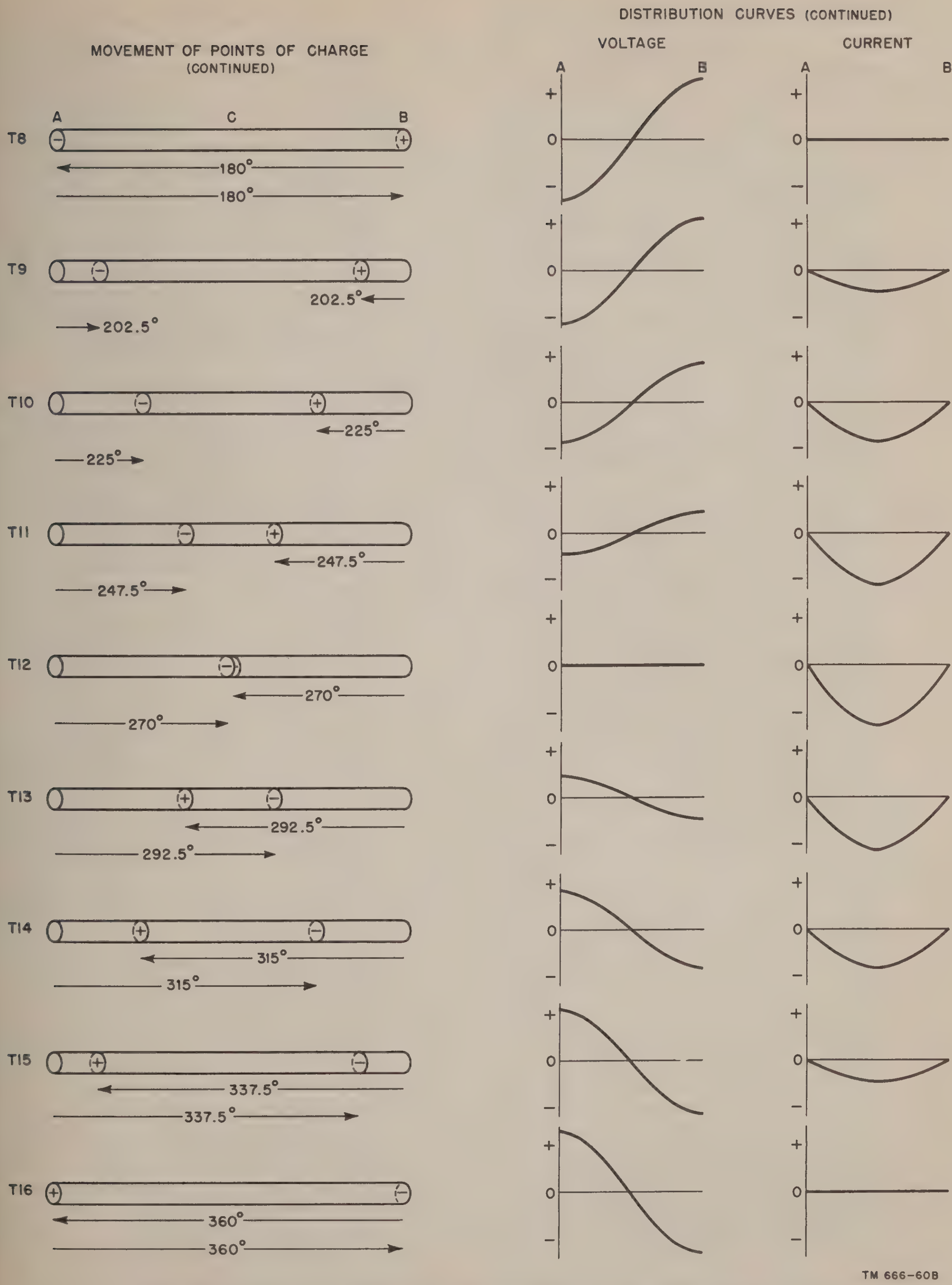


Figure 56. Voltage and current distribution in terms of positive and negative charges.

the current and voltage *at that particular time* for any point on the antenna. For example, at time T0, the positive and negative charges are at points *A* and *B* on the antenna. The voltage between these points represents a maximum difference of potential. The current, being 90° out of phase in respect to the voltage, is everywhere zero. These distribution curves are *standing waves* derived in the same manner as those discussed in the previous paragraph.

(3) The next illustration shows the position of the charges at time T1. The standing wave of current is a relative maximum at the center of the antenna. This current loop has nodes which remain at the ends of the antenna, and it is, therefore, 90° out of phase with the standing wave of voltage.

(4) At T2 and T3, the charges move closer together, and the standing wave of voltage slowly decreases in amplitude. Conversely, the current loop increases in magnitude. When the charges meet after 90° of the r-f cycle (T4), the effect is that of having the positive and negative charges cancel. The voltage loop accordingly is zero everywhere on the antenna, and the current loop rises to its maximum value, unimpeded by any charge on the antenna.

(5) At time T5, the charges have passed each other, each charge having moved past the center point of the antenna. The polarity of the voltage loops is reversed, and they build up in the opposite direction, keeping the node always at the center point of the antenna. The reversal of polarity is shown in the charge positions at T3, T4, and T5. The separation of the charges also is accompanied by a decrease in the amplitude of the current loop.

(6) From T5 to T8, the charges move out to the ends of the antenna. During this time, the voltage loops increase and the current loops decrease in amplitude. At time T8, which occurs 180° after T0 in the r-f cycle, the charges have moved to opposite ends of the antenna. Compare the picture in T0 to the picture in T8. It is seen that the negative charge is now at point A and the positive charge at point B. Since the positions of the charges have been reversed from T0 to T8, the voltage loops in T8 are 180° out of phase compared with the loops in T0.

(7) From T8 to T16 in figure 56, the movement of the charges is shown in the opposite direction, the current loop reaching a maximum at T12. When the entire r-f cycle is completed at time T16, the charges have returned to the positions they occupied at T0. The distribution curves of voltage and current also are in their original conditions. The entire process then is repeated for each r-f cycle.

b. Standing Waves of Voltage and Current.

(1) The distribution curves of the current and voltage are standing waves. This means that they are the resultants obtained by adding two traveling waves. The two traveling waves are associated with the positive and negative charges. The wave caused by the negative charge can be called the incident wave, and the wave caused by the positive charge the reflected wave. The discussion, however, is clearer when the concept of negative and positive charges is used.

(2) The positive charge above, taken at time T0 in figure 55, produces a traveling wave of voltage, shown by the dashed line in A, figure 57. The negative charge at the opposite end of the antenna produces an identical traveling wave (dash-dot curve). These two add together to produce the T0 voltage distribution curve, which is the resultant wave of *A* of figure 55. Both of these waveforms are identical, being the standing wave of voltage at time T0. All the following distribution curves of figure 57 are produced in the same manner. They are the standing-wave resultants caused by the traveling waves accompanying the charges.

(3) In *B* of figure 57, each of the traveling waves has moved 45°, the positive traveling wave moving to the right and the negative traveling wave moving to the left. This time corresponds to T2 in figure 55. The standing wave produced corresponds to the voltage distribution curve at T2. The standing waves of current are produced in the same manner.

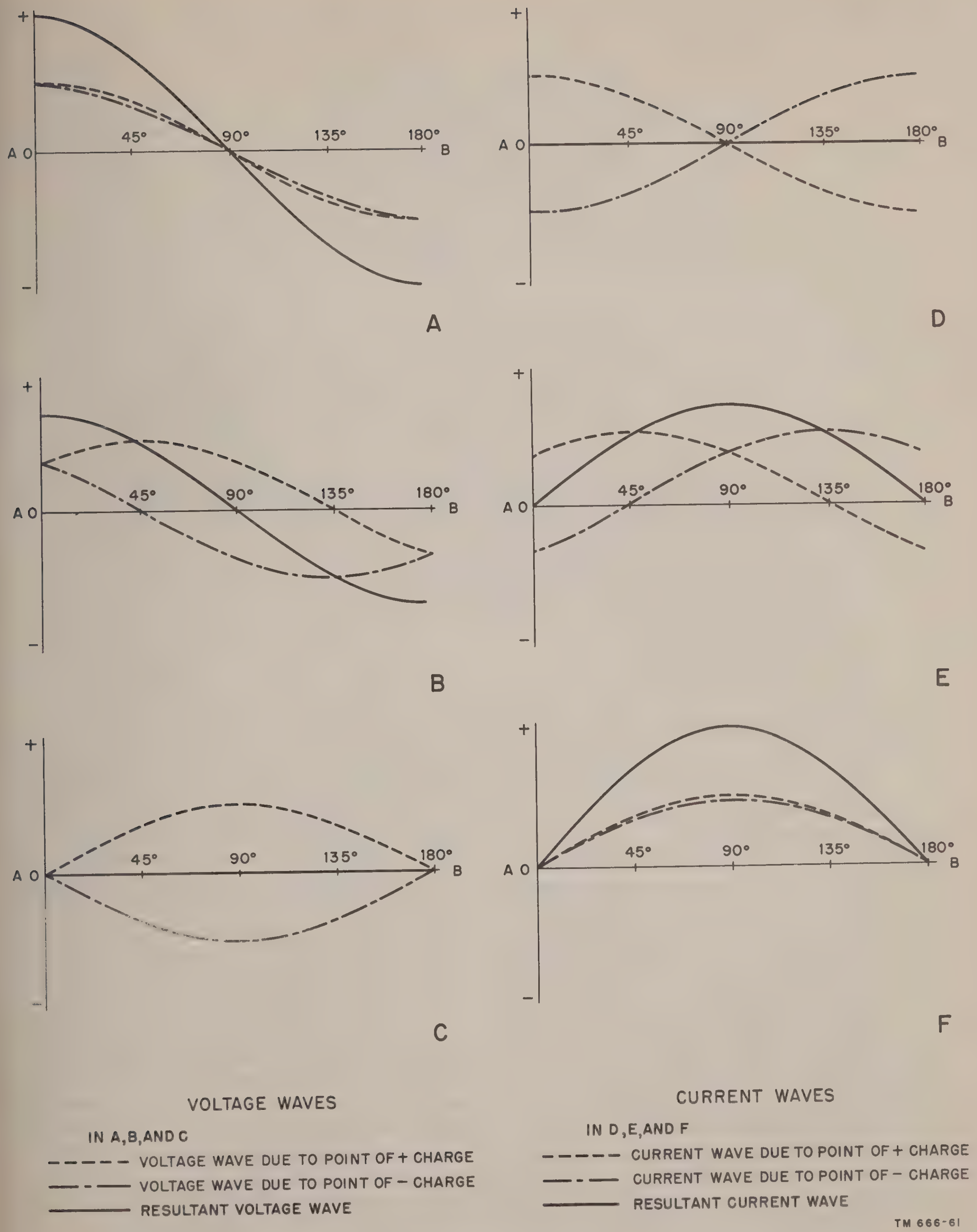


Figure 57. Standing waves of voltage and current.

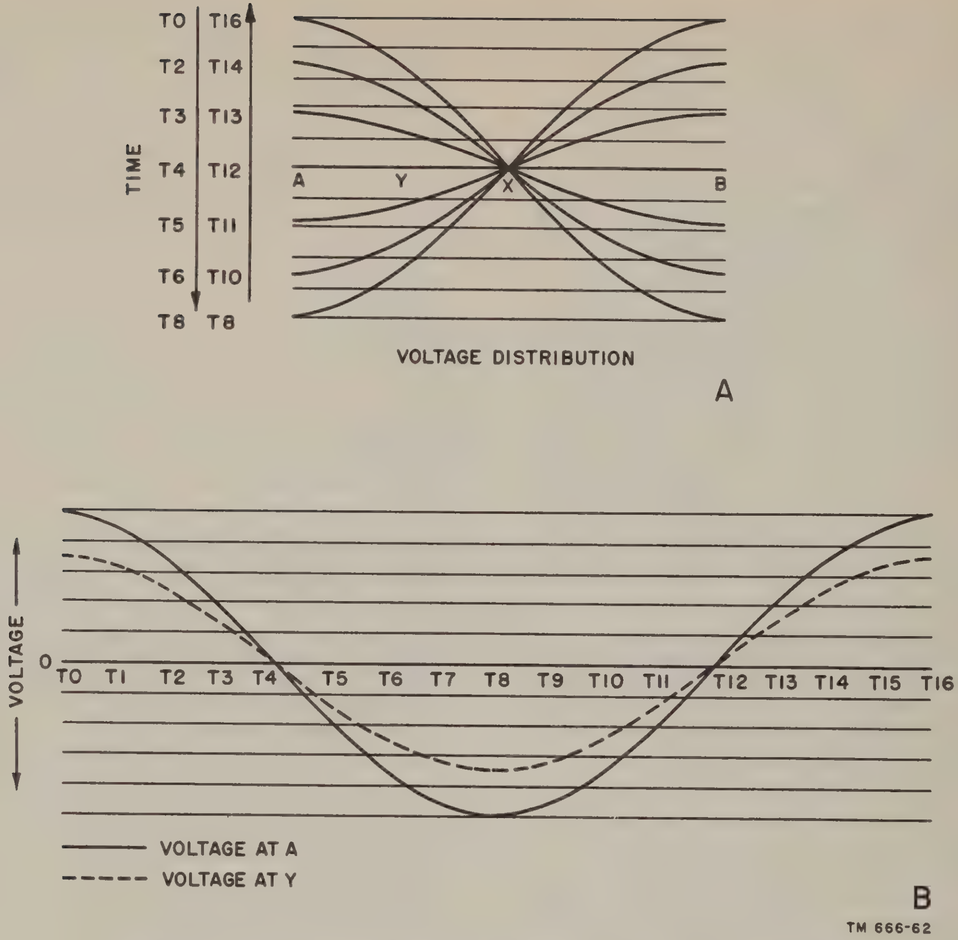


Figure 58. Standing waves of voltage at a point on the antenna.

The current curves at *D*, *E*, and *F* of figure 57 correspond to times T0, T2, and T4 of figure 55.

c. Standing Waves of Voltage.

(1) In *A* of figure 58, voltage standing waves occurring at different times are brought together on one axis, *AB*, representing a half-wave antenna. Essentially, these are the same curves shown progressively in figures 55 and 56 as voltage distribution curves. They can be used to determine the voltage at any point on the antenna at any instant of time. For example, if it is desired to know the variations of voltage occurring at point *Y* on the antenna over the r-f cycle, the variations are graphed in respect to time, as shown in *B* of figure 58. At T0 the voltage at *Y* is maximum. From T0 through T3 the voltage decreases, passing through zero at T4. The voltage builds up to a maximum in the opposite direction at T8, returning through zero to its original position from T8 to T16.

(2) Between T0 and T16, therefore, an entire sine-wave cycle, *Y*, is reproduced. This is true also of any other point on the antenna with the exception of the node at *X*. The peak amplitude of the sine wave produced at any point depends on its position on the antenna. The nearer the point is to either end, the greater its peak amplitude.

d. Standing Waves of Current. The standing waves of current occurring at various times through the r-f cycle are assembled on a single axis in figure 59. This axis, *AB*, represents the half-wave antenna. If the current variations at point *Y* from T0 to T16 are graphed in respect to time, the result is the sine wave in *B* of figure 59. This is true for any point along the antenna with the exception of the nodes at the ends. The current has its greatest swing at *X*, the center of the antenna. Comparison of the voltage varia-

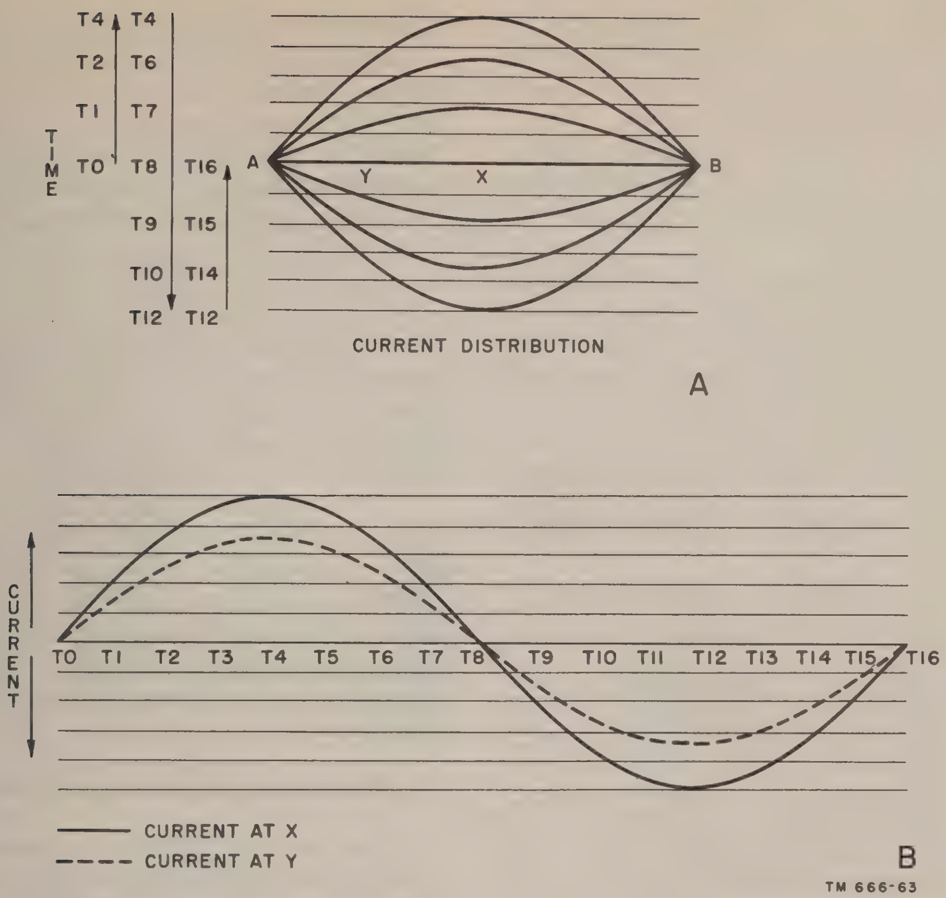


Figure 59. Standing waves of current at a point on the antenna.

tion curve (*A* of fig. 58) with the current variation curve (*A* of fig. 59) shows the voltage curve leading the current curve by 90° at *Y*. This relation can be expected on any half-wave device.

e. Measurement of Standing Waves. In figure 60, the standing waves of voltage *E*, and current *I*, are indicated along the antenna. There are current nodes at *A* and *B* and a voltage node at *X*. These standing waves are found on any half-wave antenna. A meter that indicates the effective value (0.707 of peak) of the a-c signal can be used to measure the standing waves present on the half-wave antenna.

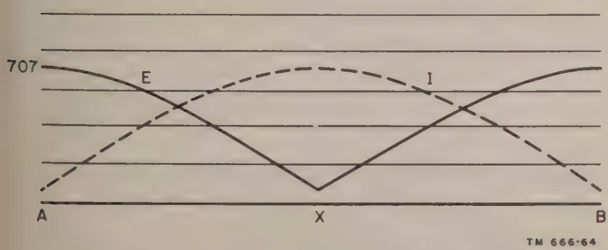


Figure 60. Standing waves as measured with a meter.

42. Velocity of Propagation and Antenna Length

a. In free space, electromagnetic waves travel at a constant velocity of 300,000 kilometers or 186,000 miles per second. The r-f energy on an antenna, however, moves at a velocity considerably less than that of the radiated energy in free space because the antenna has a *dielectric constant* greater than that of free space. Since the dielectric constant of free space (air or vacuum) is approximately 1, a dielectric constant greater than 1 retards electromagnetic-wave travel.

b. Because of the difference in velocity between the wave in free space and the wave on the antenna, the *physical* length of the antenna no longer corresponds to its *electrical* length. The antenna is a half-wavelength electrically, but somewhat shorter than this physically. This is shown in the formula for the velocity of electromagnetic waves,

$$V = f\lambda$$

where V is the velocity, f is the frequency, and λ is the wavelength. Since the frequency of the wave remains constant, a decrease in the velocity results in a decrease in the wavelength. Therefore, the wave traveling in an antenna has a shorter wavelength than the same wave traveling in free space, and the physical length of the antenna can be shorter.

c. The actual difference between the physical length and the electrical length of the antenna depends on several factors. A thin wire antenna, for example, has less effect on wave velocity than an antenna with a large cross section. As the circumference of the antenna increases, the wave velocity is lowered as compared with its free-space velocity. The effect of antenna circumference on wave velocity is illustrated in the graph of figure 61.

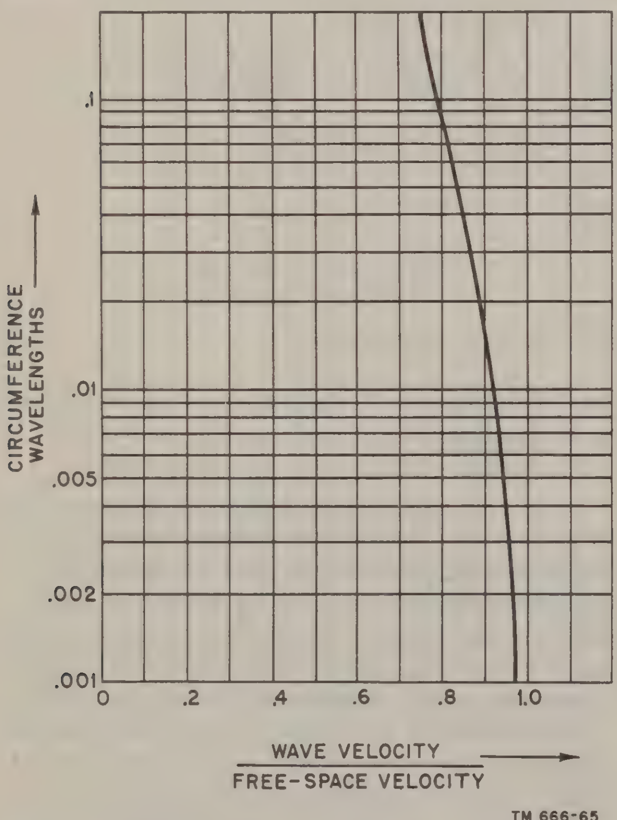


Figure 61. Effect of antenna circumference on wave velocity.

d. Other factors are involved that lower wave velocity on the antenna. Stray capacitance, for example, increases the dielectric constant and lowers wave velocity. This capacitance can be caused by the line connecting the antenna to the transmitter, the insulators used to give physical support to the antenna, or nearby objects made of metallic or dielectric materials. The change in velocity resulting from stray capacitance is called *end effect* because the ends of the antenna are made farther apart electrically than they are physically. End effect is counteracted by making the physical length about 5 percent shorter than the electrical length, as expressed in the formula

$$L=0.95(492/f)$$
$$=468/f$$

where L is the physical length in feet and f is the frequency in megacycles. This formula is accurate for all practical purposes in determining the physical length of an antenna 1 half-wavelength at the operating frequency.

e. The capacitive end effect also changes slightly the standing waves of voltage and current. When the standing waves are measured, it is found that the nodes have some value and do not reach zero, because some current is necessary to charge the stray capacitance. The standing waves measured in figure 62 show the results of end effect.

43. Resonance, Resistance, and Impedance

a. Resonance. The antenna is a circuit element having distributed constants of inductance, capacitance, and resistance, which can be made to form a resonant circuit. The half-wave antenna is the shortest resonant length of antenna. However, antennas which are 2 or more half-wavelengths also can be resonant. Such antennas are said to operate on harmonics. If an antenna is 4 half-wavelengths at the transmitter frequency, it is being operated at the fourth harmonic of its lowest resonant frequency. In other words, this antenna is a half-wavelength at one-quarter of the frequency of operation. An antenna operating on the third harmonic is shown in figure 53.

b. Resistance.

(1) A current flowing in the antenna must contend with three kinds of resistance. With the antenna considered as a radiator of energy, the power expended in the form of radiation can be thought of as an I^2R_r loss. R_r is called the *radiation resistance*. With the antenna considered as a conductor, a certain amount of energy is dissipated in the form of heat. In this I^2R_o loss, R_o is the *ohmic resistance*. There is also an I^2R loss because of the *leakage resistance* of dielectric ele-

ments, such as insulators. This R usually is included in the ohmic resistance.

(2) The purpose of the antenna is to dissipate as much energy as possible in the form of radiation. The energy dissipated by the radiation resistance, therefore, is the useful part of the total power dissipated. Since the actual power loss depends on the ohmic resistance, this resistance should be kept as low as possible. In the half-wave antenna, the radiation resistance is large compared to the ohmic resistance, and most of the available energy is radiated. The half-wave antenna is, therefore, a very efficient radiator for most purposes.

(3) For a half-wave antenna fed at the center point, the radiation resistance is equal to 73 ohms. The reference point is the center of the antenna at the time of peak current flow. Ohmic resistance is referred to this point. The total resistance is of importance in matching the antenna to a transmission line.

c. Impedance.

(1) Because the half-wave antenna has different conditions of voltage and current at different points and because impedance is equal to the voltage across a circuit divided by the current through it, the impendance will vary along the length of the antenna. If E is divided by I at each point of the voltage and current curves in figure 62, the result is the impedance curve, Z. The impedance is about 73 ohms at the center point and rises to a value of about 2,500 ohms at the ends.

(2) The impedance of the half-wave antenna usually is considered to be the impedance as *seen* by the transmitter at the input terminals. This impedance consists of both resistance and reactance. If the antenna is cut to a length of exact resonance, the reactance is zero and the impedance is purely resistive. However, if the antenna is longer or shorter than resonance, reactance is present. When the antenna is made shorter, capacitive reactance is present; when the antenna is made longer, inductive reactance is present.

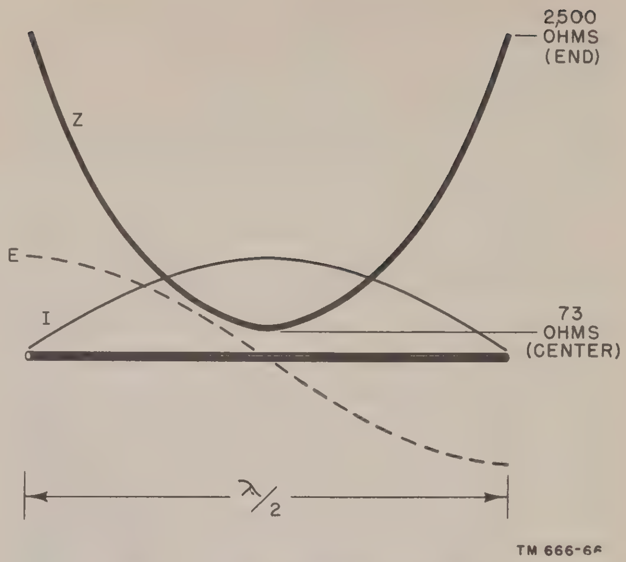


Figure 62. Impedance along half-wave antenna.

(3) The impedance at the antenna input terminals is important in terms of power efficiency. If the transmitter is feeding a nonresonant antenna, a power loss is caused by the reactive component of the antenna impedance. Conversely, if the frequency of the transmitter is changed, the electrical length of the antenna also changes. If the frequency is made somewhat higher, the electrical length is made greater, and inductive reactance is added to the impedance. If the frequency is lowered, the electrical length is shortened, and capacitive reactance is added to the impedance.

Section II. TRANSMISSION LINES

44. Introduction

a. A transmission line is a device for guiding electrical energy from one point to another. Therefore, it can be used to transfer the output of a transmitter to an antenna. Although it is possible to connect the antenna directly to the transmitter, the antenna generally is located some distance away. In a vehicular installation, for example, the antenna is mounted outside and the transmitter inside the vehicle. A transmission line, therefore, is necessary as a connecting link.

b. The transmission line has a single purpose in respect to both the transmitter and the antenna. This purpose is to transfer the power output of the transmitter to the antenna with the *least possible loss.* How well this purpose is accomplished depends on the characteristics of the transmission line used.

45. Transmission-Line Characteristics

a. Terminology.

(1) The transmission line used to couple energy from the transmitter to the antenna has an *input end* and an *output end.* The output circuit of the transmitter is coupled to the input end, also called the generator end or source. The antenna is coupled to the output end, also called the load end or the sink.

(2) The ratio of voltage to current at the input end is known as the *input impedance.* The ratio of voltage to current at the output end is known as the *output impedance.* If the line were of infinite length, the *characteristic impedance* would be the ratio of voltage to current on this infinite line. This value is a constant for a given transmission line.

(3) By comparing its electrical length to the wavelength of the energy to be transferred, a transmission line can be called *long* or *short.* It is short when its length is short compared with a wavelength, and long when its length is long compared with a wavelength. This becomes important when considering the efficiency of energy transfer through the line, because the line has *distributed constants* the effect of which increases with length.

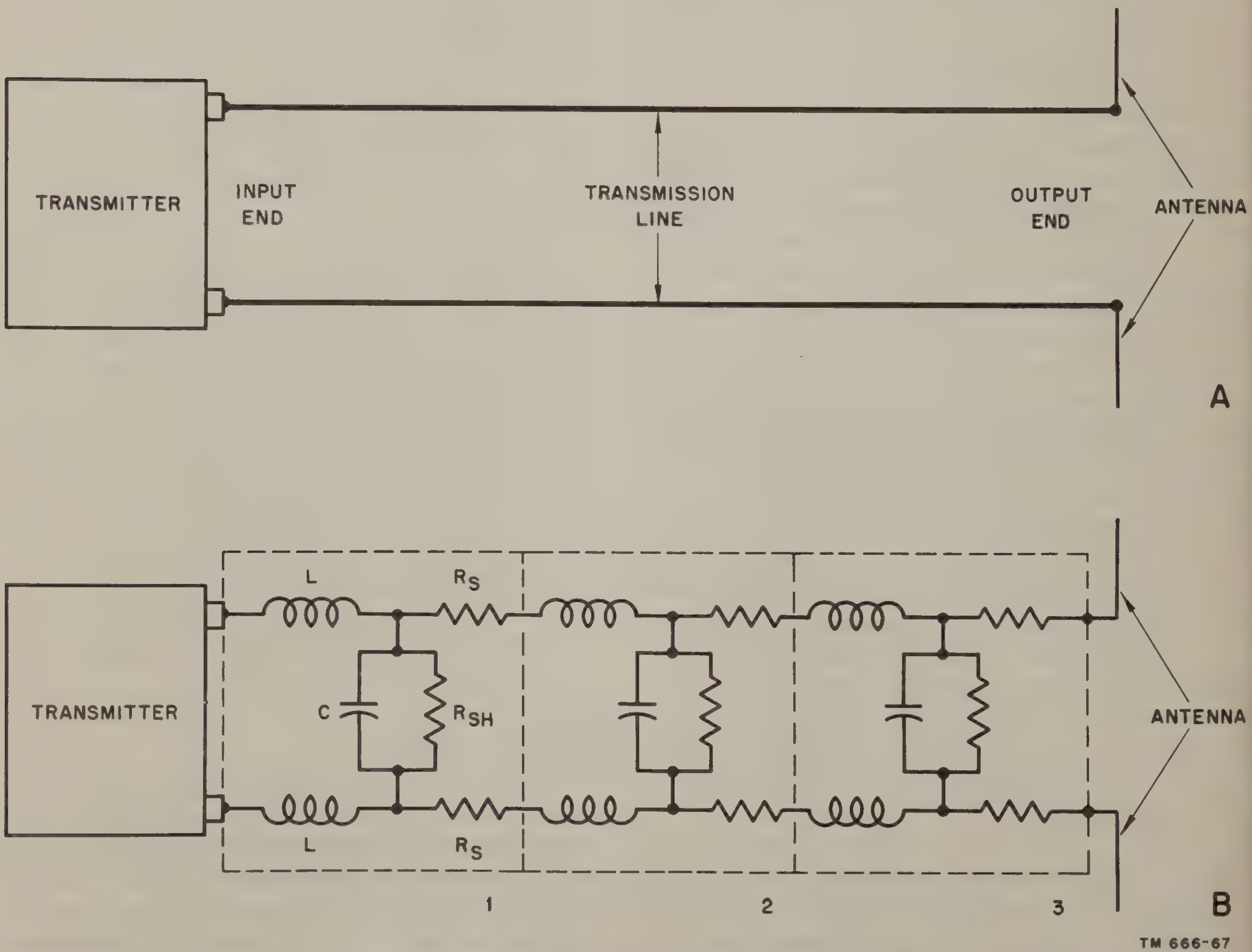


Figure 63. Basic transmission line and equivalent circuit.

b. Distributed Constants.

(1) The transmission line is essentially a four-terminal device. Two terminals (input end) are connected to the transmitter, and two terminals (output end) are connected to the antenna. Between these terminals are distributed constants of inductance, capacitance, and resistance; their values depend on the physical characteristics of the line.

(2) *A* of figure 63, shows a basic system consisting of a transmitter, two wires, and an antenna. The equivalent circuit, *B*, shows that any given section of the line has a certain amount of distributed constants which are divided into three equal sections of lumped constants. The number of sections depends on the unit of length chosen. The amounts of inductance, capacitance, and resistance depend on the length of the line, the size of the conducting wires, the spacing between the wires, and the dielectric (air or insulating medium) between the wires.

(3) These constants actually cannot be distinguished in the manner shown in *B* of figure 63. For example, the resistance is distributed uniformly along the entire length of the line and usually is measured in ohms per unit length. This is represented as R_S in section 1. There is also a certain amount of leakage resistance between the wires, represented as R_{SH}. This resistance is in shunt with the input and output ends and is the result of current leakage between the wires through the dielectric.

(4) The wires forming the transmission line also possess distributed inductance. This inductance can be seen in the action of magnetic fields set up by current flow. For example, if current flow attempts to drop to zero suddenly, the collapsing magnetic fields sustain the current for a time. The time during which the current is sustained is a measure of the distributed inductance. The distributed inductance, *L*, is considered to be in series with the line, and is measured in microhenries per unit length.

(5) The two wires substituted for the plates of a capacitor in figure 49 show an electric field produced between them when they were connected to a source of emf. This is also true of the wires that constitute the transmission line. The intensity of this electric field is a measure of the distributed capacitancy, which is expressed in micromicrofarads per unit length. These wires act as a capacitance, *C*, shunted across the line (*B* of fig. 63).

c. Characteristic Impedance. In addition to having the distributed constants, a transmission line has a *characteristic impedance*. If an *infinitely long* transmission line is assumed, then the characteristic impedance, Z_o, determines the current that flows when a given voltage is applied. This impedance is purely resistive, and it is constant for a given transmission line. The characteristic impedance is important in determining how well energy is transferred from the source to the load. For the infinitely long line, all of the energy is sent out on the line, and none returns to the source. If a finite line is terminated with a purely resistive load equal to Z_o, the source *appears to see* an infinitely long line, and all the energy passes into the line. If the line is terminated in any other load, energy is reflected back to the source.

d. Attenuation and Losses. The ideal transmission line has no losses. It transfers all the energy available at the transmitter to the antenna. Actual transmission lines, however, dissipate power in three ways.

(1) *Radiation.* The transmission line tends to act like an antenna. Radiation losses can be considerable with certain types of lines.

(2) *Heating.* The resistance of the conductors dissipates a certain amount of power in the form of heat (I^2R loss). At higher frequencies, an appreciable amount of heat loss can result from skin effect. An I^2R loss also results from leakage between the conductors (dielectric loss). Heat loss increases with lines having a lower characteristic impedance because of the higher currents that are permitted to flow.

(3) *Reflection.* It has been explained that a load other than Z_o reflects energy back along the line. This results in the reflection loss explained below.

e. Reflection of Energy.

(1) In discussing the infinitely long antenna wire, it was pointed out that energy injected by the transmitter results in traveling waves. The same can be said

of an infinitely long transmission line. Traveling waves of voltage and current continue to move down the line so long the line has no end.

(2) Assume a finite line where the two conductors terminate abruptly, as if they were cut. Traveling waves reaching this open end are reflected in the same manner and this results in the formation of standing waves of voltage and current that are out of phase, just as on the antenna. The reflected waves represent energy that is not absorbed by the load but is reflected back along the line. This is undesirable in a transmission line, where the object is to transfer as much energy as possible to the load.

(3) If energy is reflected, standing waves are formed, which means a changing ratio of voltage to current along the line, and therefore a changing line impedance. If all energy is reflected from the output end and none is absorbed by the load, the impedance is purely reactive all along the line. If some energy is absorbed and some reflected, the line impedance either can be resistive (more or less than Z_o) or can have both resistive and reactive components.

f. Z_o and Reflection.

(1) There can be no reflected waves, and hence no standing waves, on an infinitely long line. However, an infinitely long line has an impedance of Z_o. When the transmitter injects energy into a line impedance equal to the characteristic impedance, there are no standing waves and *no reflections*. The transmitter can *appear to see* an infinitely long line if a resistive load equal to the characteristic impedance is placed across the output end. Consequently, a line terminated in this manner causes no reflection of energy and no standing waves. This results in a maximum transfer of energy from transmitter to antenna.

(2) Inductance, capacitance, and resistance found in a transmission line are distributed uniformly along its length. Therefore, no reflection of energy takes place unless the impedance at some point on the line is different from that caused by the distributed constants. The impedance seen by the transmitter can be changed by changing the load. The traveling waves reaching the load suddenly encounter an impedance different from that along the line, resulting in the formation of standing waves and reflection of energy. Reflections occur so long as the load differs in any way from Z_o.

g. Basic Line Terminations. The load which terminates the transmission line can vary from zero to infinity. It can be either resistive or reactive, or both. A line terminated in a resistance equal to Z_o is said to be *properly terminated*. In this case, the line appears to be infinitely long looking from the source toward the load, and no reflection occurs. *Any other load* causes reflection and the formation of standing waves. The two extreme cases of line terminations are shorted or open output terminals. In the first, the short represents a load equal to zero. Since a zero load differs from the characteristic impedance, standing waves are set up on the transmission line. This short-circuited line is known as a *closed-end* line. If the output terminals are left open, the load is infinite, also resulting in standing waves. This is called an *open-end* line. In either the closed-end or the open-end line discussed in (1) and (2) below, no power is delivered to the load (antenna). The use of either line results in complete reflection of energy back to the source (barring line losses).

(1) The standing waves created on a closed-end line are shown in *A* of figure 64. The line used is a half-wavelength at the operating frequency. For simplicity, the waves are shown using the top wire as a zero baseline. Because of the short across the output terminals, the current loop is maximum at that point, and the voltage is zero. A quarter-wavelength back along the line, there is a current node with a maximum on the voltage loop. A half-wavelength back (at the input terminals), there is a voltage node with a current loop (maximum negative). The voltage and current ratio, and therefore, the impedance, continually change along the line. At the load, the impedance is zero. At the current node, the voltage is maximum and the impedance infinite (there is no current flow). At the source, the current again is maximum and the impedance zero. At the load end, therefore, no power is

absorbed ($P = I^2Z = I^2 \times 0 = 0$), all of it being reflected back along the line. At the source, the transmitter is working into zero impedance, and there is no expenditure of power. (In the actual case, however, some loss is caused by numerous factors, such as radiation or heat.) Consequently, no energy is transferred to the antenna if there is a short across the output terminals of this line.

(2) In a half-wavelength section of open-end line, the load, Z_L, is infinite, and creates the standing waves shown in *B* of figure 64. Although the standing wave of voltage is maximum at the open end, current is zero. At a quarter-wavelength back, the current is maximum, the voltage is zero, and the impedance is zero. At the source, the current again is zero, the voltage maximum, and the impedance infinite. Since the transmitter is working into an infinite impedance, no current flows and no power is expended ($P = I^2Z = 0 \times Z = 0$).

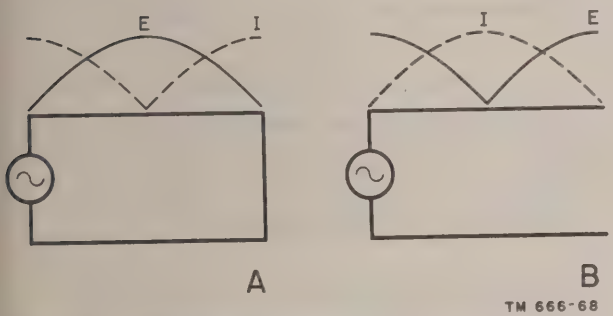


Figure 64. Standing-wave formation on closed- and open-end half-wave transmission lines.

(3) If a transmission line is terminated in either a low or a high resistance (fig. 65), as compared with Z_o, the effect is similar to an open or a closed end. The low resistance termination causes standing waves, which have nodes and loops at the same points as with a closed end. The *amplitudes* of the standing waves are lower, however, and the nodes no longer reach zero. This is because *some* power is absorbed by the low resistance, although most of it is reflected back to the

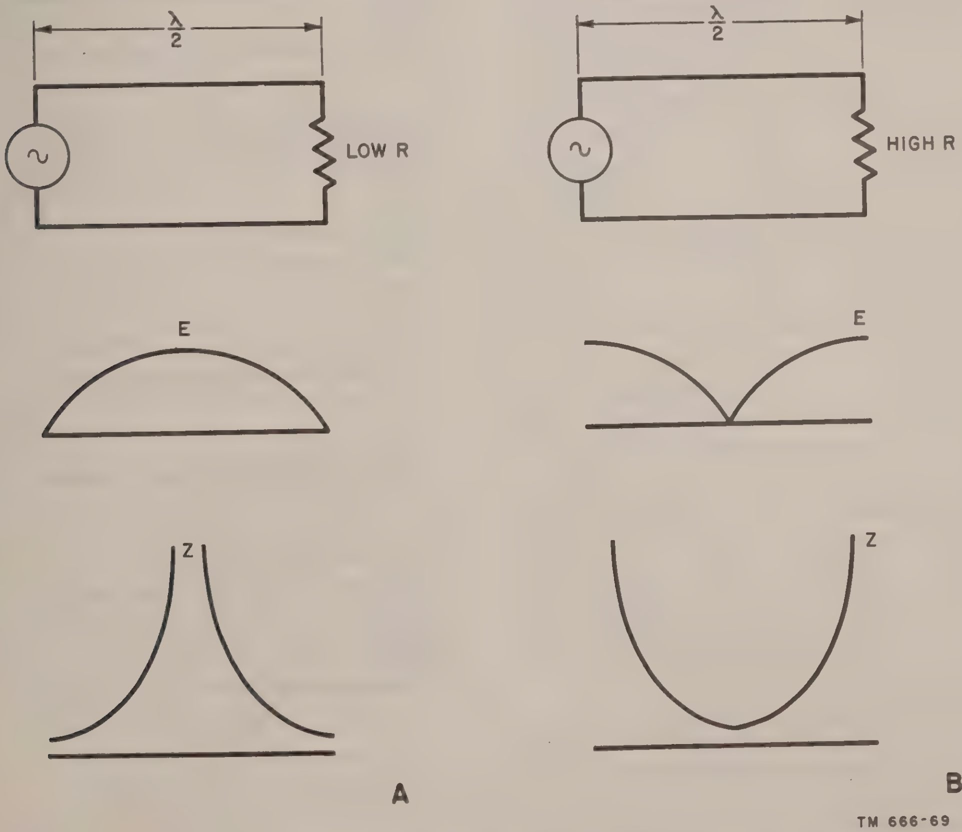


Figure 65. Half-wave lines terminated in low and high resistance.

source. Compare A of figure 65, with A of figure 64.

(4) In B of figure 65, the line is terminated in a high resistance. This produces standing waves similar to those produced by an open end, as in B of figure 64. Again, the difference is only in standing-wave amplitude. Figure 66 shows that the standing waves decrease in amplitude when the characteristic impedance is approached from either side. Values of resistive load ranging from a closed to an open end are noted.

(5) The effects of purely reactive loads are shown in figure 67. In A, a half-wave section of line is terminated in a purely capacitive load. Compare the standing waves in this case to the standing waves resulting from an open-end line. The standing waves are shifted an eighth-wavelength forward from the source and the current leads the voltage, the latter condition resulting in an input impedance consisting of capacitive reactance. As the capacitance is increased, the voltage node moves nearer and nearer the output end. The result of having a transmission line terminated in capacitance is to increase the effective electrical length. This is the same type of change that results from end effect on an antenna. The effect is equivalent to adding an open-end section of line which is less than a quarter-wavelength long.

(6) Terminating the line in an inductance results in the standing waves shown in B of figure 67. Compared to the open-end termination, the current wave is shifted an eighth-wavelength back toward the source. This results in an input impedance consisting of inductive reactance (voltage leads current). Placing an inductance across the output is equivalent to adding a closed-end section of line less than a quarter-wavelength long. Decreasing the inductance moves the voltage node nearer the output end.

h. Other Line Terminations.

(1) It is possible to connect either the generator or the load at other points along the transmission line besides the ends. So long as the line is not terminated in a resistive load equal to Z_o, standing waves

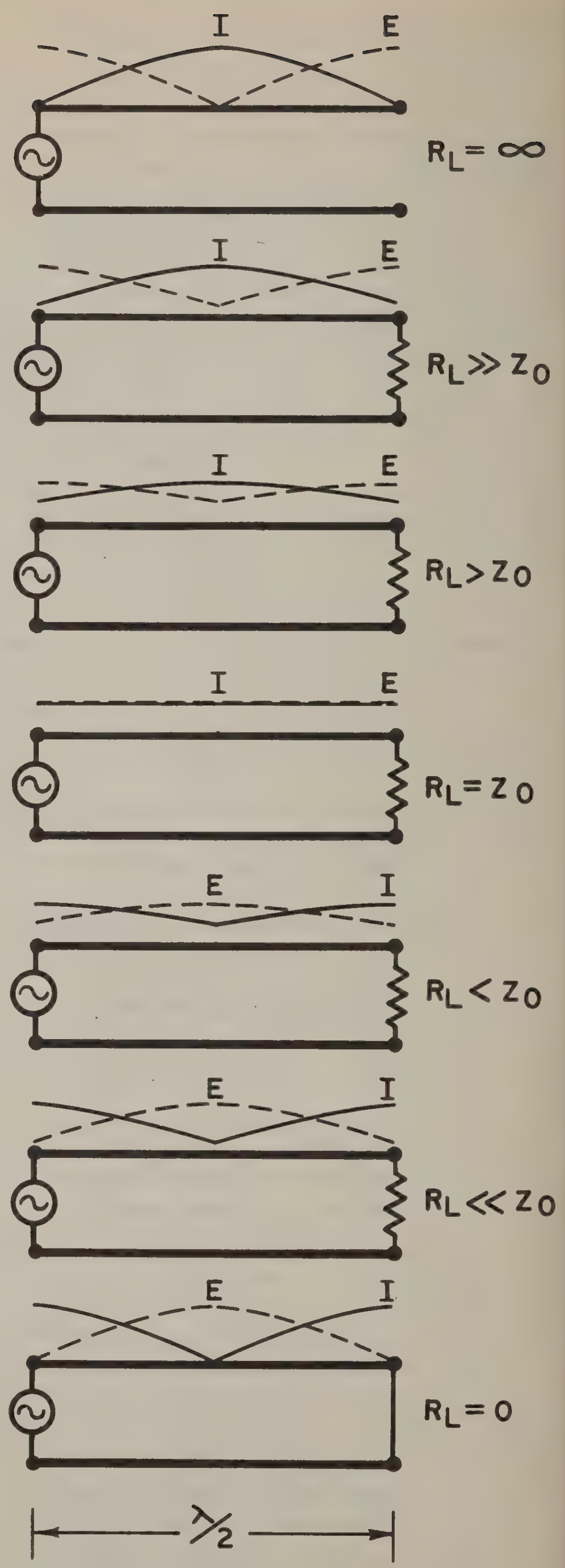


Figure 66. Varying resistive load from zero to infinity on the half-wave line.

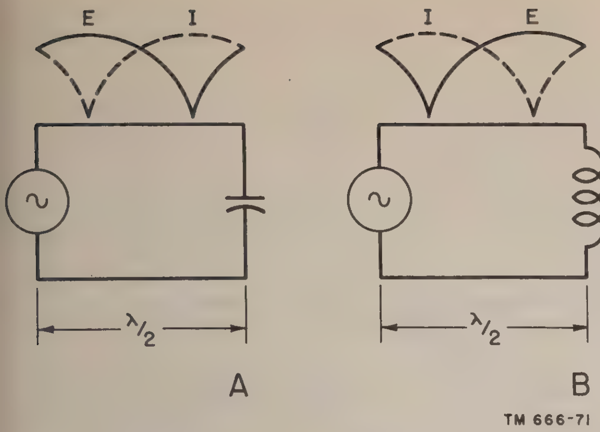


Figure 67. Half-wave lines terminated in capacitance and inductance.

exist. This results in a line impedance which varies all along the line. The generator then can be connected to work into different impedances at different points.

(2) Assume an open-end half-wavelength line (fig. 68). The impedance curve along the line not only changes its value in ohms, but also changes in *type* of impedance. If the generator is connected a distance between a quarter- and a half-wavelength from the load, the input impedance consists of inductive reactance. Connecting the generator to the same point on the shorted line in *B* of figure 68 results in an input impedance consisting of capacitive reactance.

(3) If the generator in *A* of figure 68 is connected exactly a quarter-wavelength from the open end, the input impedance is a very low resistance. The equivalent lumped-constant circuit, however, is not simply a small resistor, but a *series-resonant* circuit. In other words, the transmission line has resonant lengths like an antenna. If the generator in *B* is connected a quarter-wavelength from the load, the input impedance consists of a very high resistance. The equivalent circuit in this case is a *parallel-resonant* circuit.

(4) It is possible to connect the load at different points along the line. In figure 69, the load is connected a sixteenth-wavelength from the end of a shorted quarter-wavelength line. The generator is connected at a point of high voltage and low

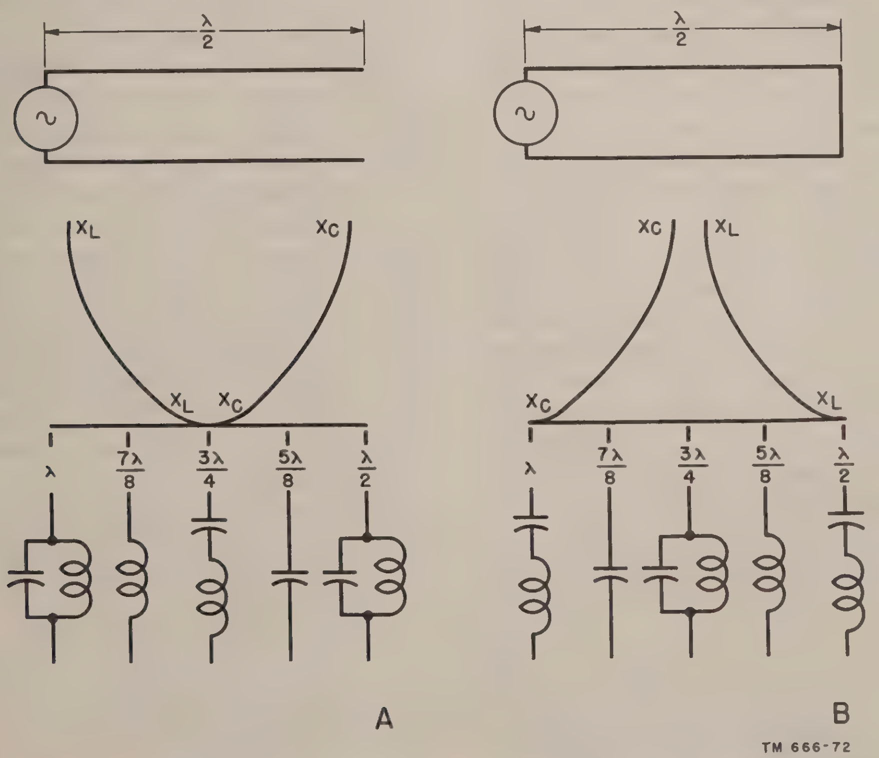


Figure 68. Line impedance changes on a half-wave open-end line and on a half-wave closed-end line.

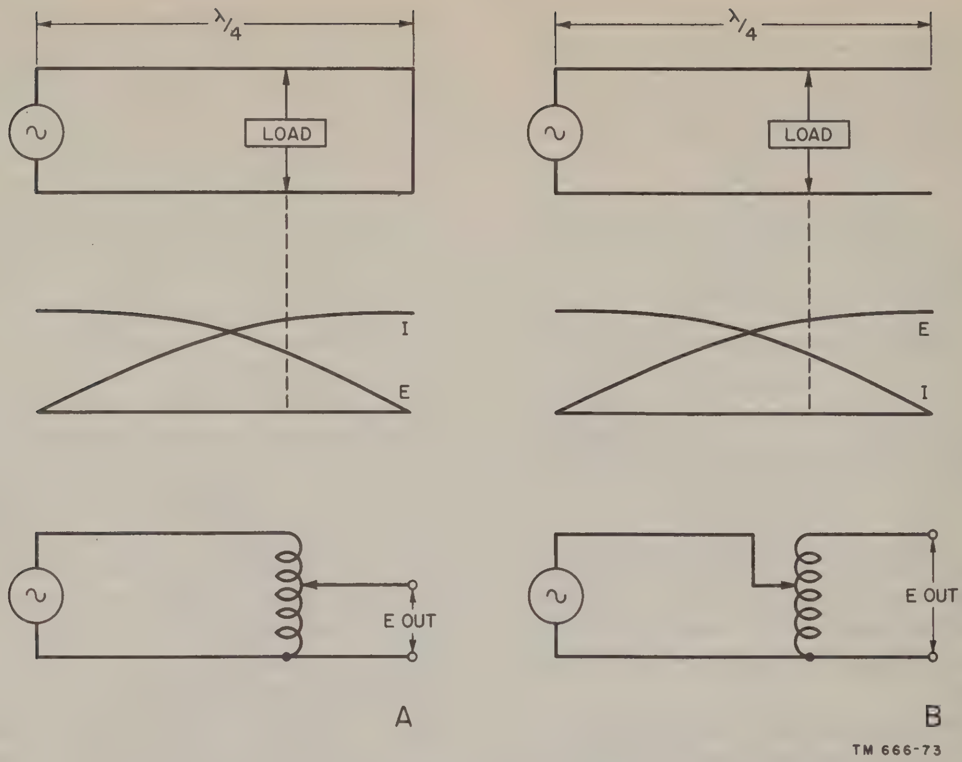


Figure 69. Open and closed lines as step-up and step-down transformers.

current. The load is connected to a point of relatively lower voltage and higher current. The equivalent circuit for the line, therefore, is a *step-down transformer*. The equivalent of a *step-up transformer* can be obtained by connecting the load to the same point on an open-end quarter-wavelength line, as in *B* of figure 69.

i. Changing Line Length.

(1) For open- and closed-end lines, the impedance seen by the source is given in figure 70. In *A*, different lengths of open-end line are given. These vary from less than a quarter-wavelength to 1 wavelength. The impedance seen by the source is repeated in half-wave steps. For example, the series-resonant circuit seen at 1 quarter-wavelength is seen again at 3 quarter-wavelengths. It also is to be seen at the fifth and seventh quarter-wavelengths, and for every length measured in odd quarters. On the other hand, the generator sees a parallel-resonant circuit at a half-wavelength, 1 wavelength, and 3 half-wavelengths and so on. In other words, the input impedance consists of a parallel-resonant circuit on open-end lines an even number of quarter-waves long.

(2) In *B* of figure 70 different lengths of shorted line are given. For shorted lines, series resonance occurs at even quarters and parallel resonance at odd quarters. This is the reverse of the situation with open-end lines. For lengths of line shorter and longer than even or odd quarters, the input impedance is indicated as either inductive or capacitive. The generator also can be inserted at different points along any of these lines. The input impedance then is simply the line impedance at that point.

j. Standing-Wave Ratio.

(1) The actual loads connected to the transmission line usually have both resistive and reactive components. The result is the formation of standing waves on the line. Considering the standing wave of voltage, the ratio of maximum to minimum voltage along the line is called the *standing-wave ratio*. This ratio also can be obtained by measuring maximum and

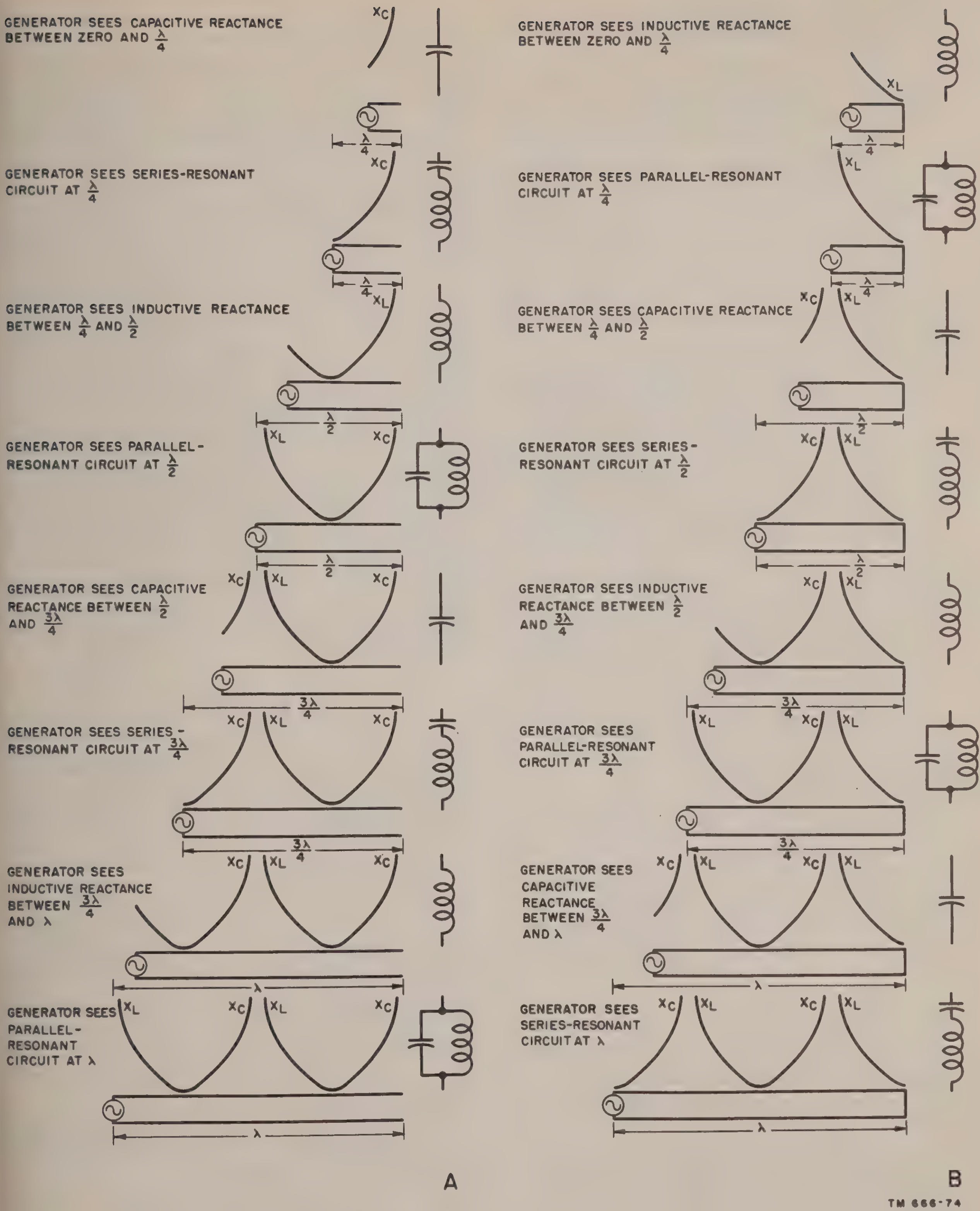


Figure 70. Changing line length changes the impedance seen by source.

minimum current along the line. The standing-wave ratio provides a measure of the energy reflected.

(2) When the line is terminated in a resistance equal to Z_o, the maximum and minimum values of current are the same. The SWR (standing wave ratio) is 1 to 1, or 1. In this condition the load is said to be *matched* to the line. All of the energy is absorbed by the load (neglecting line losses), and there are no standing waves. Such a line is called *flat*, since the impedance is the same value, Z_o, all along the line.

(3) If standing waves occur on the line with a given load, the SWR is a measure of the degree of *mismatch* between load and line. For example, assume that a resistive load of 500 ohms is used to terminate a line with Z_o of 50 ohms. If the SWR is measured, it is found to be 10. This is the same as dividing 500 by 50.

k. Resonance.

(1) If a load resistance equal to Z_o terminates the line, then the line is matched, or flat. There are no reflections, and the SWR is unity. By definition, a matched line is *nonresonant*. This means that there is no reflection of energy and there are no standing waves, resulting in maximum transmission of energy.

(2) Assume a section of line which is terminated in a load *not* the same as Z_o. This line has standing waves which are greater than 1, indicating the degree of mismatch. This line is called *resonant*. Depending on the type of load and the length of line used, the transmission line can be represented by a series- or a parallel-resonant circuit.

(3) The nonresonant, or matched, line is used principally in fixed or semifixed operation, since its design and construction take into consideration a great many factors. Even in fixed installations, however, only a need for very high efficiency warrants the use of a nonresonant line. The resonant line, on the other hand, is simple in construction and flexible in operation, and therefore, is used in most field or mobile installations. Although a maximum SWR exists on a resonant line, it still can be used with relatively high efficiency.

l. Impedance Matching. Assume that a transmission line has a characteristic impedance of 100 ohms. This line must be used to feed an antenna with 75 ohms of resistance and 30 ohms of inductive reactance at the operating frequency. Since a mismatch occurs if the line is connected directly to the antenna, an intermediate element must be used between the line and the antenna. Such an element is called an *impedance-matching device.* For this purpose, a carefully constructed section of transmission line can be used. This is possible because a line exhibits an impedance which varies with length. If the proper length is selected, this length then can serve as the matching element.

m. Velocity of Propagation. Wave travel on the transmission line is retarded in the same manner as on the antenna. Consequently, the electrical length and the physical length are not the same. The electrical length depends directly on the dielectric medium, the physical dimensions of the conductors, and the space between them. All the factors on which the electrical length depends can be reduced to a single constant factor for a specific type of line. The electrical length then can be expressed as—

$$l = 246\ k/f$$

where l is the electrical length in feet, k is the factor for the specific line, and f is the frequency of operation in megacycles. Typical values of k range from 0.56 to 0.975.

46. Types of Transmission Line

Until now, only one type of transmission line has been discussed. This is the type using two parallel conductors, uniform in every dimension. So far as general theory is concerned, the previous discussion applies to all types of transmission lines. Physically, however, transmission lines differ considerably in their construction and specific characteristics. The various types are discussed below.

a. Single-Wire Line. This is the simplest type of transmission line. A single-wire conductor links the transmitter to the antenna. The return path completing the circuit is ground. Because there is only one metallic conductor, the line is *unbalanced.* This condition leads to large radiation losses, which is a definite disadvantage. Another disadvantage is the lack of a constant

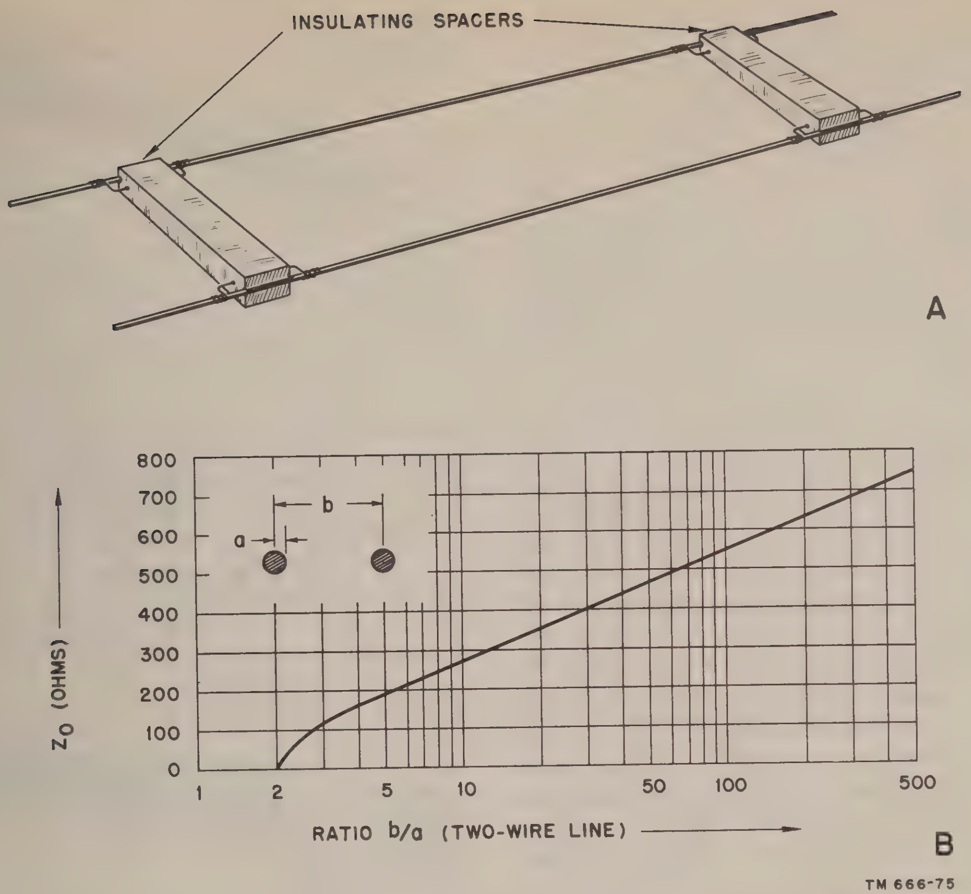


Figure 71. Variation in Z_o with changes in b/a ratio, open two-wire line.

physical relationship between wire and ground, which leads to a varying characteristic impedance, making the line difficult to match to the antenna. Because of these two disadvantages, the single-wire line is used rarely. It is found where its advantage of easy installation outweighs its disadvantages.

b. Open Two-Wire Line.

(1) Because it uses two parallel conductors, this is called also the *parallel-conductor line*, and because the dielectric medium is air, it is known also as an *open-wire line* (fig. 71). The construction and installation of the open two-wire line are nearly as simple as for the single-wire line. Although the balanced conductors act to reduce radiation loss, the balance is critical, and nearby metallic objects tend to unbalance the line and cause large radiation losses. The two wires used in this line are kept at a constant distance from each other by means of insulating bars called *spacers*, or *spreaders*, shown in A of figure 71. The actual distance used between the conductors depends on the impedance required, the diameter of the wire, and the frequency of operation.

(2) The characteristic impedance of a two-wire line is relatively constant. For a two-wire line having air as a dielectric medium, Z_o is given by the formula

$$Z_o = 276 \log_{10} \frac{b}{a}$$

where b equals the space between the conductors measured from their centers and a equals the radius of the wire used. This formula is sufficiently accurate provided that the ratio b/a is 4 or greater. The graph in B of figure 71, demonstrates the variation in Z_o produced by changing the ratio, b/a.

(3) Currents flow through the two parallel conductors in opposite directions. If

the two currents are exactly 180° out of phase, the fields nearly cancel and the radiation loss approaches zero. At relatively low frequencies, this condition can be approached. As the frequency of operation is raised, however, the two currents tend to be more and more out of phase, causing considerable radiation loss. The loss can be reduced by moving the conductors closer together. Because of radiation, the distance between the conductors should never exceed 0.01 λ, where λ is 1 wavelength at the operating frequency.

(4) Moving the conductors closer together lowers the characteristic impedance of the line. This can be seen from the equation given above. In order to have a relatively high impedance and close spacing, it is necessary to reduce the size of the conductors. Reduction in size, however, decreases the power capabilities of the conductors. The higher the frequency of operation, the more difficult these problems become. A practical limit to the use of two-wire lines having air as the dielectric medium is reached at approximately 200 mc.

c. *Insulated Two-Wire Line.*

(1) Instead of having air as a dielectric medium, the two-wire line can be incased in a solid dielectric. This type of line has several advantages over the open line. Installation is simplified considerably because of its flexibility. For example, it is difficult to run the open-wire line around a corner without changing the spacing between the conductors. In the insulated type, the dielectric is solid enough to keep the conductors evenly spaced, but flexible enough to bend easily around corners.

(2) In one type of insulated line, the two conductors are molded into the edges of a plastic ribbon called polyethylene (fig. 72). The dielectric losses are

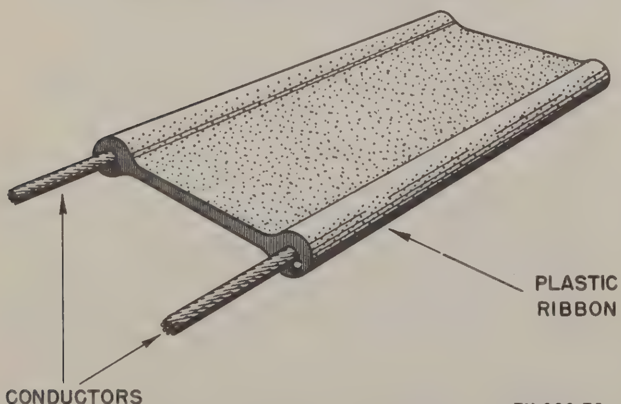


Figure 72. Insulated two-wire line.

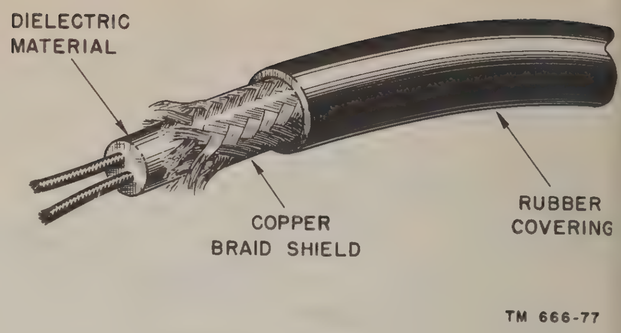


Figure 73. Shielded pair.

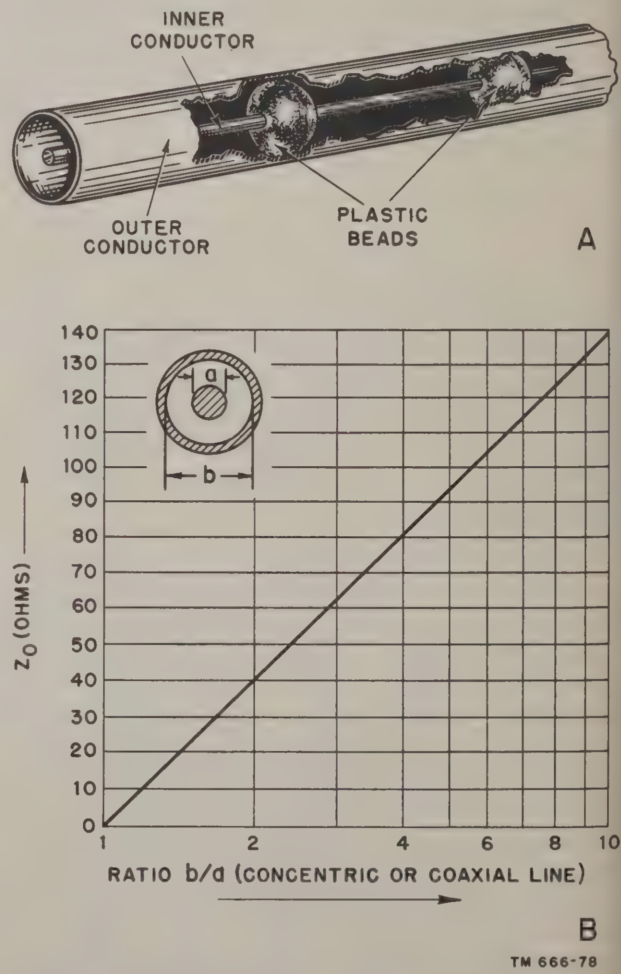


Figure 74. Variations in Z_o with changes in the b/a ratio, open coaxial line.

higher than in a comparable open-wire line, and the higher dielectric constant lowers the characteristic impedance.

d. Shielded Pair. A further development of the insulated two-wire line is the shielded pair (fig. 73). The two parallel conductors are imbedded in a solid dielectric, such as the plastic copaline. The insulated pair then is inclosed in a tube made of braided copper. The entire assembly is given a weatherproof coating. The principal advantage of the shielded pair over other types of two-wire lines is its low radiation loss. This is true because the shield provides a uniform ground for both conductors, resulting in a well-balanced line. Furthermore, the shield provides protection from stray pickup in the presence of external fields.

e. Twisted Pair. If two insulated wires are twisted together, a flexible transmission line results without the use of spacers. This type is limited to use as a short untuned line because of its high losses. It should not be used at frequencies above 15 mc.

f. Coaxial Lines.

(1) It is possible to place one conductor *inside* the other to form a transmission line. Such a line is called coaxial, or concentric. The open line (air dielectric) is shown in A of figure 74. Usually, it consists of a wire conductor placed inside a flexible metal tube which serves as the second conductor. The inner wire is fixed along the central axis of the outer tube by spacers, usually plastic beads. The open coaxial line is used to provide efficient operation at relatively high frequencies. There is little radiation loss from this type of line because the outer conductor confines radiation to the space *inside* the line. External objects consequently have no effect on transmission, making this line definitely superior to the two-wire type. Instead of air, the line can be filled with a flexible, plastic dielectric, forming a solid, coaxial line which has the advantage of greater flexibility compared with an open coaxial line. The use of a solid dielectric, however, increases the dielectric losses.

(2) The characteristic impedance of the open coaxial line can be calculated from the formula,

$$Z_o = 138 \log_{10} b/a$$

where b equals the inner diameter of the outer conductor and a equals the outer diameter of the inner conductor. Variations in Z_o with changes in the ratio b/a are given in the graph shown in B, figure 74, which includes open coaxial lines. The formula for Z_o of a solid coaxial line is given by

$$Z_o = \frac{138}{\epsilon} \log_{10} \frac{b}{a}$$

where ϵ is the dielectric constant of the dielectric material used. The other quantities (b and a) are the same as for the open coaxial line. If ϵ is equal to 1, then the two formulas become identical. From both formulas, it can be seen that a high ratio of b/a means a high Z_o, and conversely, a low ratio of b/a means a low Z_o.

Section III. BASIC FEEDER SYSTEMS

47. Introduction

The transmission line used to couple the transmitter to the antenna sometimes is called a *feeder*. Because two general types of transmission line are used (resonant and nonresonant), methods of feed can be divided into two classes—tuned (resonant) and untuned (nonresonant or matched). Both types of line involve a transmitter, means for coupling the transmitter to the line, the transmission line, means for coupling the line to the antenna (including an impedance matching device if necessary), and the antenna itself.

48. Transmitter-to-Line Coupling

a. Transmitter Coupling to Untuned Lines.

(1) On the untuned line, the SWR is 1.5 or less, and the line is considered properly terminated. For a single-wire feeder, two types of transmitter coupling are shown in A and B of figure 75. In A, the matched line is coupled capacitively

to a tap on the coil in the output circuit of the final amplifier. The tap is adjusted for maximum power transfer. Although this method has the advantage of simplicity, it allows a great deal of harmonic radiation from the antenna. In *B*, a link is used to couple the transmitter output circuit to the feeder input circuit. The coils forming the links can be connected by a low-impedance section of line. This allows the transmission line to be moved a distance from the transmitter. This method is relatively simple and efficient, permitting little harmonic radiation.

(2) The coupling used with two-wire systems depends in part on whether the transmitter output circuit is single-ended or double-ended. It also depends on the input impedance of the two-wire feeder. If the impedance is low and the output circuit is single-ended (unbalanced), then the circuit in *C* can be used. A more flexible coupling arrangement is shown in *D*. This link circuit permits coupling to a high- or low-impedance two-wire feeder from the single-ended output circuit.

(3) When the output circuit of the transmitter is double-ended (balanced), the two-wire feeder can be coupled capacitively to the output tank, as in *E*. This method usually is found with open two-wire lines. A link arrangement, as shown in *F*, also is available for balanced output

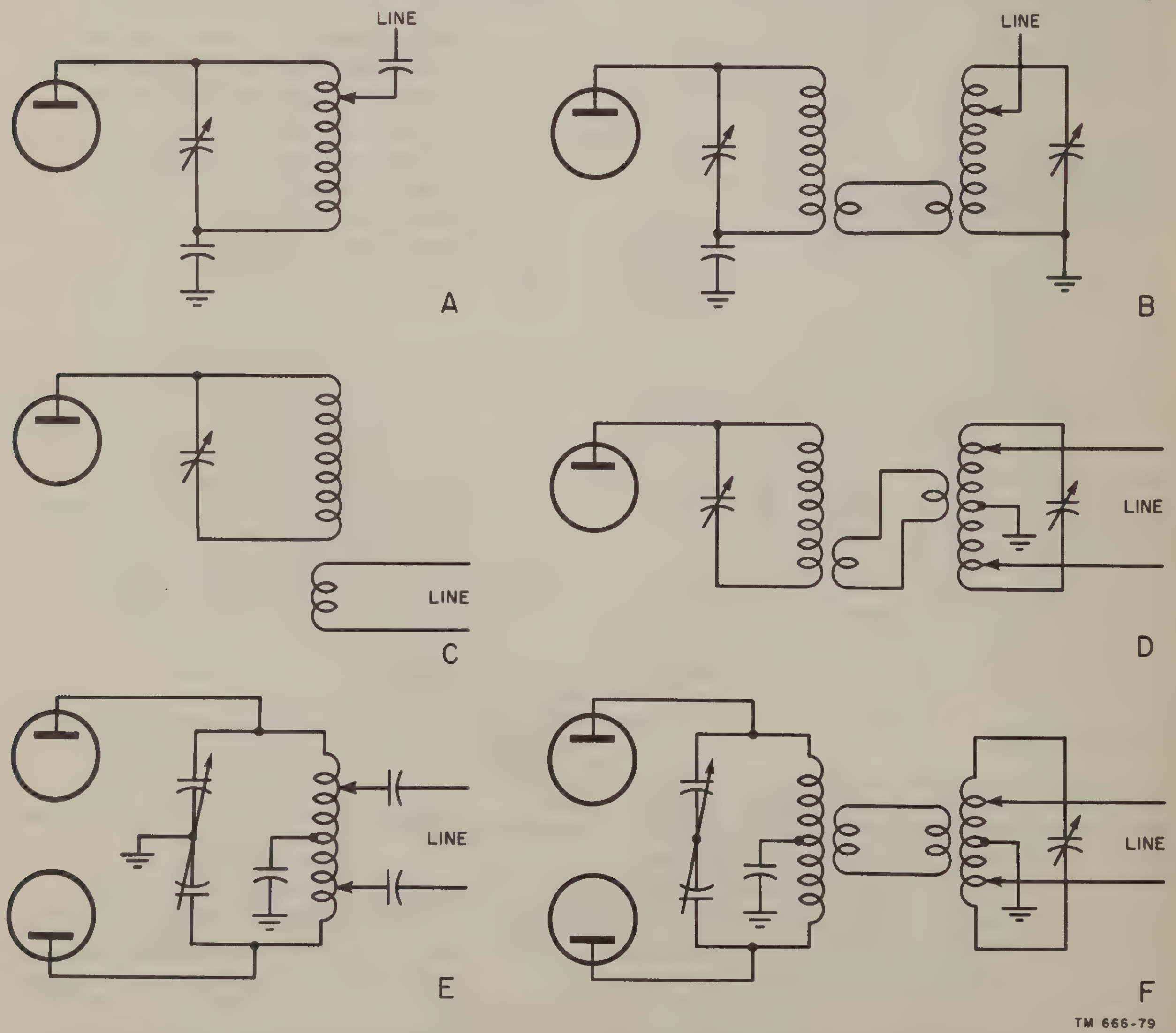


Figure 75. Various methods of coupling the transmitter to untuned transmission lines.

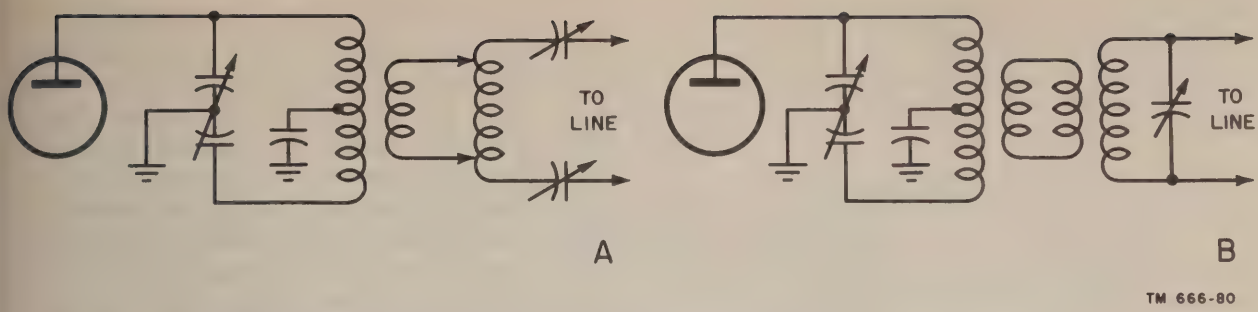


Figure 76. Two methods of coupling the transmitter to tuned transmission lines.

circuits. The line taps in both cases are placed symmetrically in respect to the center of the coil.

b. Transmitter Coupling to Tuned Lines.

(1) If a resonant transmission line is used, the type of coupling depends on whether the line input impedance is the equivalent of a series- or a parallel-resonant circuit. The circuit in *A* of figure 76, is an arrangement used with a line presenting a low impedance to the transmitter. The extra link serves to reduce harmonic radiation from the antenna.

(2) An arrangement that can be used for either series- or parallel-tuned lines is shown in *B*. In this circuit, the link reduces harmonic radiation to a minimum. Except for the method of employing the link, the circuits in *A* and *B* are almost identical.

c. Pi-Section Coupling Network. The pi-section circuit is a versatile network which can be used with both tuned and untuned lines. It also can be used with balanced and unbalanced final-amplifier circuits over a wide range of line impedances. A single pi-section is used for coupling to a single-wire feeder (*A* of fig. 77). For a two-wire feeder, a double pi-section provides the necessary coupling, as in *B*.

49. Methods of Feed

a. Line Conditions.

(1) Between the transmitter coupling network and the antenna input terminals, certain factors must be taken into consideration with regard to the transmission line. These factors apply equally to both tuned and untuned lines, and they deal with the problem of minimizing radiation loss from the line.

(2) A minimum of radiation loss is attained when the fields surrounding the two conductors forming the line are equal and opposite in phase, and hence cancel each other. In this condition, a transmission line is called *balanced*. If the line is unbalanced, excessive radiation loss occurs. The radiation loss is directly proportional to the amount of line unbalance. Common causes of line unbalance are—

(*a*) Unequal size, length, or spacing of the conductors.

(*b*) Unequal loading of the two conductors. This can result either from the antenna, or from coupling between one conductor and a nearby conducting surface.

(*c*) Acute angle in the line.

(3) Various methods are available for bal-

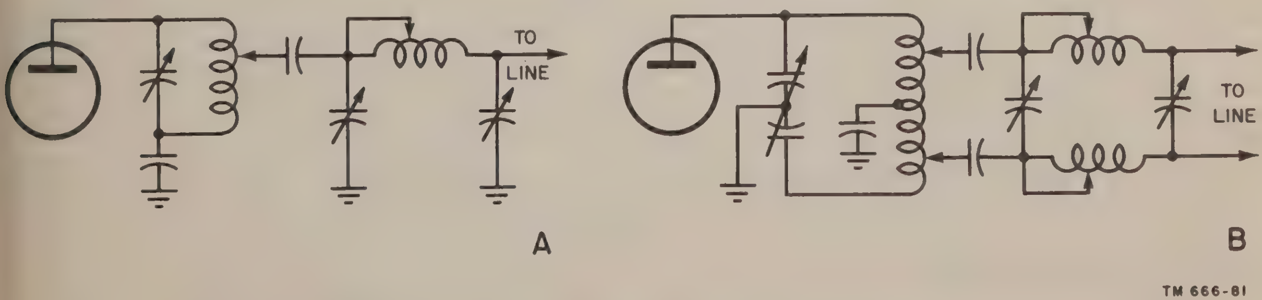


Figure 77. Pi-section coupling to tuned or untuned lines.

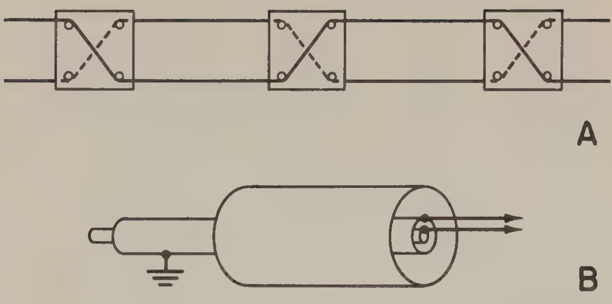


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Figure 78. Devices for balancing transmission lines.

ancing different types of transmission lines. Open-wire and shielded-pair lines have constant dimensions. If the line is a wavelength long, it usually is balanced. If an open-wire line longer than 1 wavelength is used, transposition blocks can be substituted for spacers. The positions of the conductors are reversed at regular intervals by means of these blocks (*A* of fig. 78). This serves to balance the line to ground and nearby objects.

(4) The properties of a quarter-wave section of line can be utilized to balance unequal line currents in the transmission line proper. The balancing section used with a coaxial line, as in *B*, is called a *bazooka*. It serves to make the impedance of the outer conductor equal to that of the inner conductor. If the unbalance is 10 percent or less, the line can be considered balanced for all practical purposes.

b. Feeding the Antenna. Two important factors must be considered in answering the question of how to connect the line to the antenna. An antenna at resonance has standing waves on it, presenting a varying impedance along its length. For maximum transfer of energy, the impedance at the output end of the line must match the antenna input impedance. One factor to consider, therefore, is the antenna impedance. Another factor is the type of antenna used. Methods of feed are divided into two classes, tuned and untuned, corresponding to the two classes of transmission line. If it is no longer than 1 wavelength, a resonant line works with relative efficiency. If it is longer, a matched line should be used.

50. Tuned Methods of Feed

a. Although the resonant line can have the same physical construction as the nonresonant line, standing waves are present on the resonant type. Since standing waves are present on the antenna, so far as the transmitter is concerned the antenna is merely an extension of the transmission line.

b. For all practical purposes, there are two points at which a resonant line can be used to feed a half-wave antenna. The point of highest impedance occurs at either end; the point of lowest impedance occurs at the center. If the antenna is a half-wavelength at the operating frequency, voltage loops occur at its ends and a current loop occurs at its center. If this antenna is fed at one end, it is being fed at a point of high impedance (about 2,500 ohms) and, also, at a voltage loop. If it is fed at the center, the connection is to a low-impedance point (about 73 ohms), which is also a current loop in this case.

c. An open-end resonant line can be either an odd or an even number of quarter-wavelengths. If it is an odd number, it acts as an impedance transformer. If it is an even number, it has the same input and output impedance. Either of these types can be connected to the center or the end of the half-wave antenna.

d. The four possible arrangements for feeding the half-wave antenna with tuned lines are shown in figure 79. In *A*, the antenna is *center-fed*. The impedance curve for the antenna shows that the antenna impedance, Z_A, is low at this point. The output impedance, Z_T, of the line, therefore, must be low. Since the line used is an even number of quarter-wave lengths, a low output impedance results in a low input impedance. This determines the type of transmitter-to-line coupling. A series-resonant circuit is used to provide the necessary low-impedance match. The arrangement in *A* also is called *current-fed*, since the point of feed occurs at a current loop.

e. In *B* of figure 79 the antenna is *end-fed*. The antenna therefore is being fed at a point of high Z_A. In order to obtain a high Z_T, the even quarter-wave length line is coupled to the transmitter by means of a high-impedance, parallel-resonant circuit. This type of feed results in an unbalanced line condition, and little radiation from the line occurs *provided that* the antenna is cut to a resonant length. An antenna far from resonance causes serious line radiation loss. The end-fed half-wave antenna is more common, and sometimes is referred to as *Zepp-fed*.

f. By comparison, center feed is a better arrangement than end or Zepp feed. In the center-fed

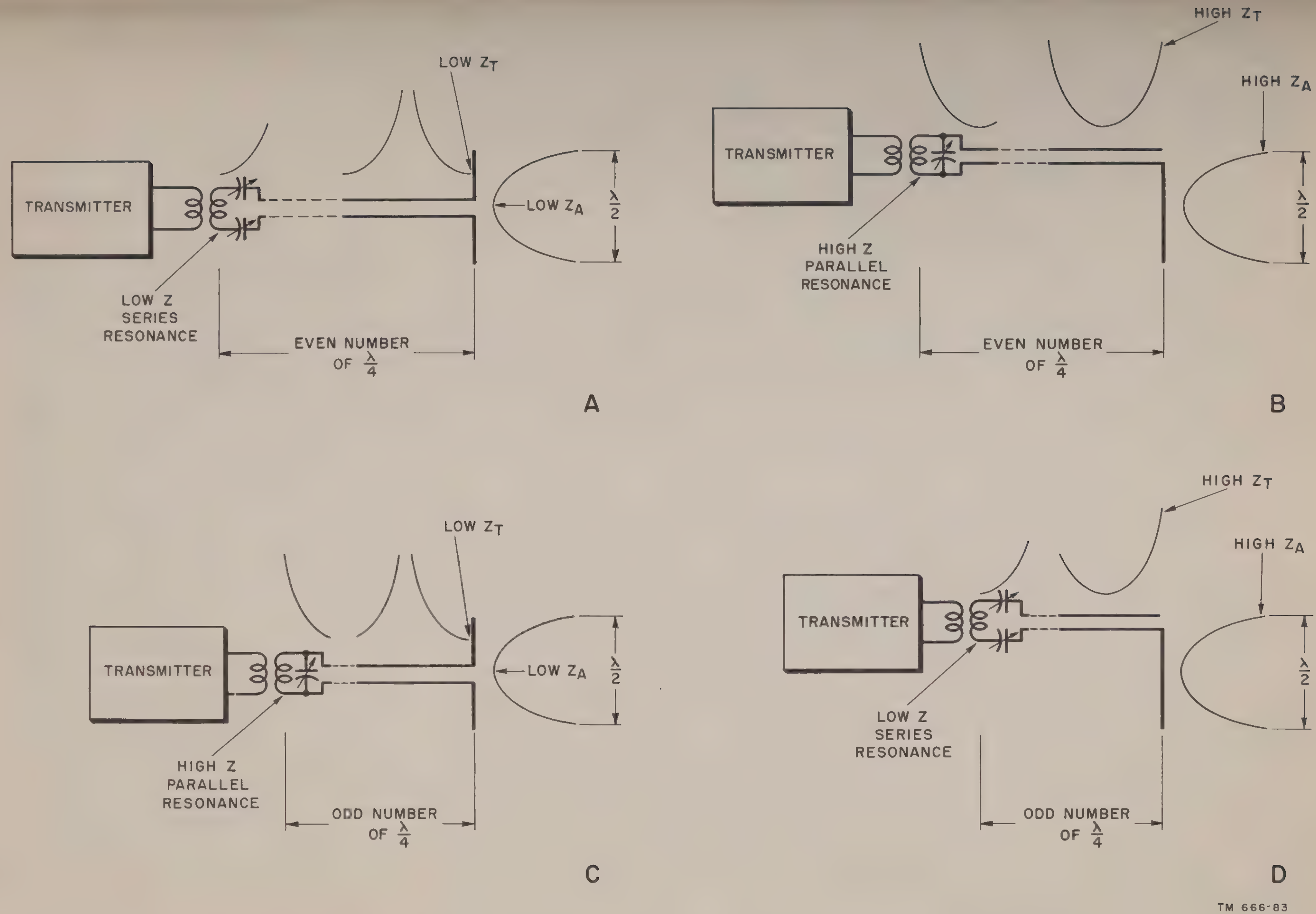


Figure 79. Four arrangements for feeding the half-wave antenna by means of tuned lines.

method, equal lengths of the antenna are added to each side of the line. Even if the antenna is actually not at resonance, the line remains near a balanced condition, and there is little line radiation loss. The symmetry of the center-fed method allows the antenna to be used over a wide frequency range, since it does not have to be near resonance to prevent line radiation loss.

g. The center-fed antenna using a tuned line an odd number of quarter-wavelengths is shown in *C* of figure 79. The distinguishing feature of this length of line is its impedance transforming action. A low impedance across the output terminals is reflected as a high impedance at the input terminals. The antenna in *C* is being fed at a point of low impedance. The resulting high impedance reflected at the input end necessitates the use of a high-impedance, parallel-resonant circuit for coupling to the transmitter. If the same line is used to end-feed the antenna, as in *D* of figure 79, the high Z_A is reflected as a low input impedance. A series-resonant circuit, therefore, is used for coupling to the transmitter. As in *B*, end feed results in a condition of line unbalance which must be kept below 10 percent.

51. Untuned Methods of Feed

a. General. For all practical purposes, a nonresonant transmission line is defined as a line with SWR of 1.5 or less. To obtain this low standing-wave ratio, the line must be terminated in an impedance very close to its characteristic impedance. The antenna impedance may vary considerably from this value. Consequently, an impedance matching device sometimes must be inserted between the line and the antenna. The input impedance of this device matches the characteristic impedance of the line, and its output impedance matches the antenna impedance.

b. Single-Wire Feed.

(1) The single-wire feeder can be used as a nonresonant line to feed the resonant half-wave antenna. For simplicity of construction, an impedance-matching device generally is not used. The characteristic impedance of this line ranges from 500 to 600 ohms. Since the antenna impedance varies from 73 ohms at the center to 2,500 ohms at the end, by connecting the line to a suitable point between the end and the center, an impedance match can be made which results in a relatively flat line. This type of connection is called *off-center feed* (*A* of fig. 80).

(2) The impedance point on the antenna which matches approximately the characteristic impedance of the line occurs about one-half of a half-wavelength from the center of the antenna. A precaution to be observed in bringing the feeder to the antenna is to keep the two elements at right angles to each other for at least one-third wavelength. This serves to prevent antenna coupling to the line.

(3) The off-center feed method just described is limited in use, despite its simplicity, because it requires the presence of a highly conductive ground return, which

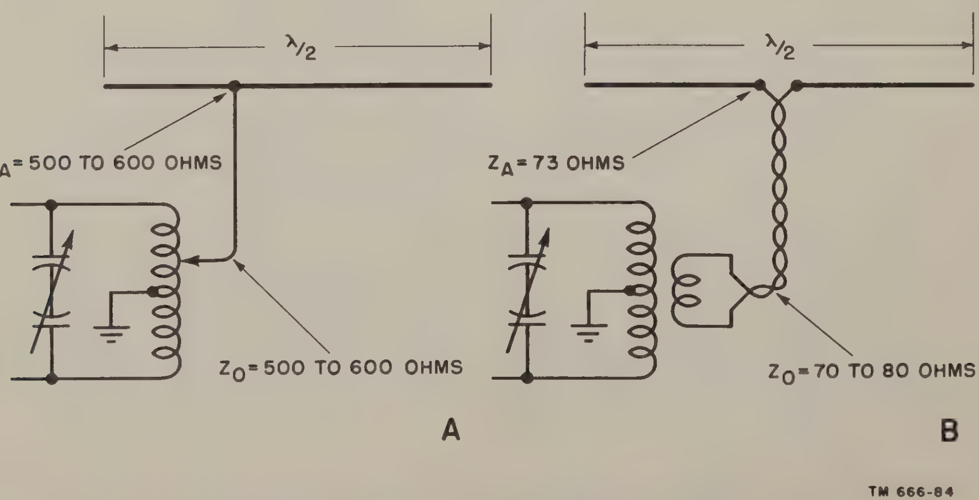


Figure 80. Single-wire and twisted-pair feed systems.

serves as the line return to the tank. This coupling occurs through the antenna-to-ground capacitance, and it requires a well grounded tank circuit. Another disadvantage is the excessive radiation loss from a single-wire feeder, since there is no parallel conductor to cancel its radiation field.

c. Twisted-Pair Feed. An emergency method for center-feeding a half-wave antenna (*B* of fig. 80) uses a twisted-pair line, the characteristic impedance of which is approximately 70 to 80 ohms. The line in the figure is matched to the antenna. If Z_O is less than Z_A, the ends of the line are spread, or *fanned*, to get the correct match. This follows from the principle that increasing the space between the conductors increases the antenna impedance seen between the terminals. This method normally is not used because of the high line losses associated with the twisted pair. In emergencies, however, the twisted pair forming a lamp cord or a field telephone wire can be used as a transmission line.

d. Two-Wire Feed Using Delta Match.

(1) A common system for feeding the half-wave antenna uses a balanced open-wire transmission line. Because of constructional difficulties, the open two-wire line usually cannot have a characteristic impedance to match the antenna input impedance. A practical line of this type has a Z_O of 400 to 700 ohms. If this line is used to center-feed a half-wave antenna having a 73-ohm input impedance, some type of impedance transformation is necessary. A method similar to *fanning* the twisted pair is used. In this case, it is called a *delta match.*

(2) An example of the use of a delta match is illustrated in figure 81. The delta match is obtained by spreading the transmission line as it approaches the antenna. Assume that the line has a characteristic impedance of 600 ohms. The antenna impedance at its center is 73 ohms. The delta section therefore must have an input impedance of 600 ohms to terminate the line properly. Proceeding from the center to either end, a point is passed where the impedance equals the impedance at the output terminals of the delta section. The delta section then is connected this distance on either side of the center of the antenna.

(3) Electrically speaking, the delta section is actually part of the antenna. The delta, therefore, introduces a radiation loss, which is one of its disadvantages. Another disadvantage is that cut-and-try methods must be used to determine dimensions *A* and *D* of the delta section (fig. 81). Since both *A* and *D* can be varied, adjustment is difficult. The advantage of the delta section is that it permits the use of a balanced transmission line. This means that there is a minimum of line radiation, which allows the mounting of other lines and antennas nearby with minimum effect. A group of antennas using deltas is shown in *B* of figure 81. Such a group is known as an *antenna park*, or an *antenna farm.*

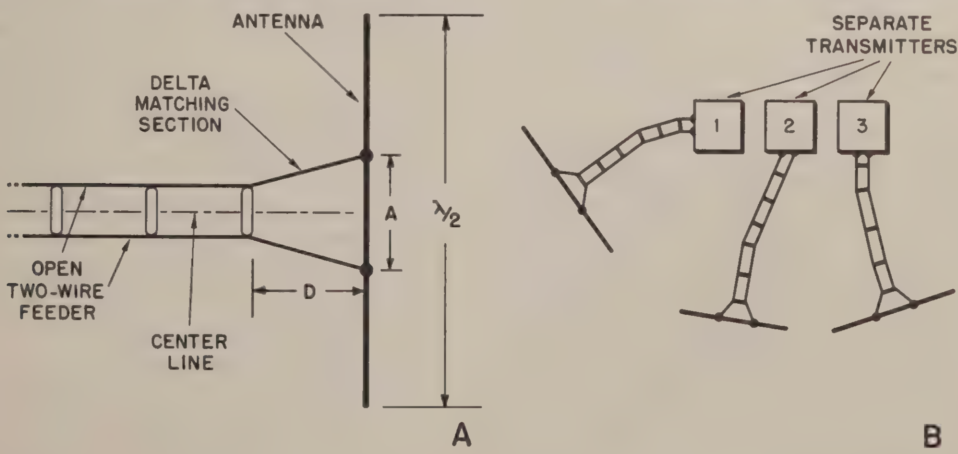
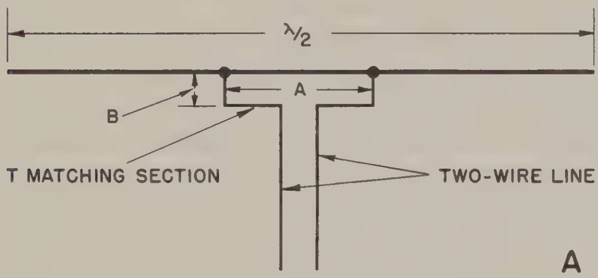


Figure 81. Delta-matched antenna and antenna park.

e. Two-Wire Feed Using T Match.

(1) A method of feed having some advantages over the delta-section method uses a *T* match (*A* of fig. 82). The essential difference between the delta and the *T* is in the shape of the matching section. When the antenna consists of a tubular conductor, the *T*-match method is easier to construct than the delta section. Furthermore, its dimensions are not nearly as critical.



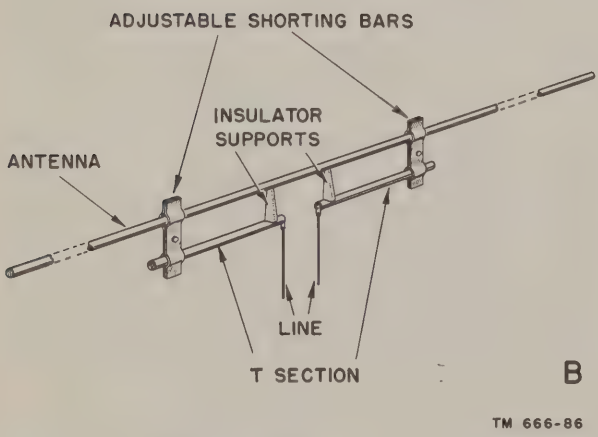


Figure 82. T-matched antenna showing T-matching section.

(2) A sketch of the physical appearance of a two-wire line feeding a *T*-matched antenna is shown in *B* of figure 82. In this arrangement, insulators can be used to support the assembly, and the line can be connected to the matching section by means of simple soldering lugs. The shorting bars permit dimension *A* to be adjusted for the best possible match. The radiation loss of the *T* section is less than that of the delta section. It must be borne in mind, however, that the *T* match also is part of the radiating element and *not* part of the nonresonant feeder.

f. Two-Wire Feed Using J Match. Still another method for feeding the half-wave resonant antenna with a nonresonant line is by means of the *J*-matched section (fig. 83). The assembly consists of a shorted quarter-wave section of transmission line end-feeding a half-wave antenna. A shorted quarter-wave section of line acts as an impedance transformer. A high impedance is seen at the open end, and this end accordingly is connected to the high-impedance end of the antenna. The impedance of the line is relatively low compared to the open end of the matching section. Consequently, the lines are connected near the shorted end of the *J* match, and are made adjustable for optimum performance. The *J*-matched antenna is in wide use in mobile installations, where simplicity and ease of operation are important.

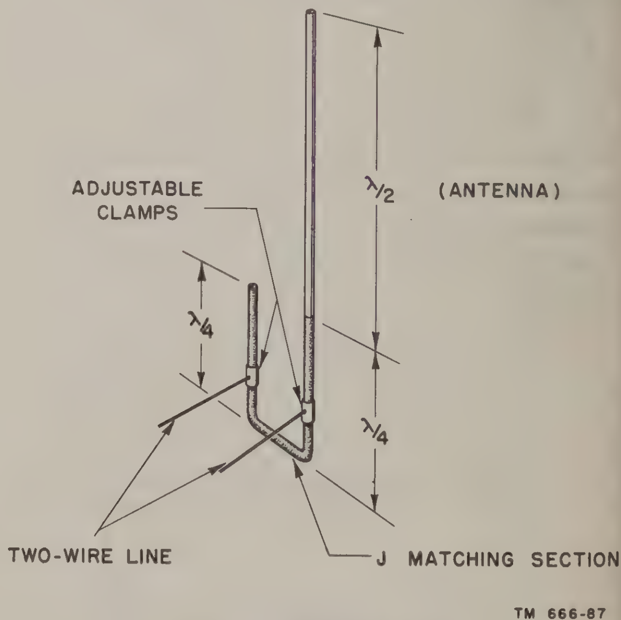


Figure 83. J-matched antenna.

g. Two-Wire Feed Using Stub Matching.

(1) A method of feed which uses sections of transmission line to connect a nonresonant line to the antenna is known as *stub matching.* The stub usually is a quarter-wave section of open or shorted line, although longer stubs can be used. In figure 84, two types of stub matching are shown. One uses the open stub, in *A*, and the other the shorted stub, in *B*.

(2) Assume that a 600-ohm nonresonant line is used to center-feed a half-wave antenna

with input impedance of 70 ohms. The stub to be used therefore must have high input impedance and low output impedance, as shown in *A* of figure 84. One end of an open quarter-wave stub is connected to the low-impedance antenna terminals. From transmission-line theory, it is known that a quarter-wave line acts as an impedance transformer. The impedance along this stub rises to a maximum at the open end. At some point along the stub, the impedance matches that of the line. In the case given, this point occurs a short distance from the antenna terminals, and the transmission line is connected to the stub at this point.

(3) A shorted quarter-wave stub can be used, as in *A*, to end-feed a half-wave antenna. As in *B*, the line is connected to the stub near the low-impedance end. This type leads to a certain amount of unbalance in loading the transmission line which should not exceed 10 percent.

(4) If the line cannot be brought close enough to the antenna to use a quarter-wave stub, longer stubs can be used. For example, any open stub an odd number of quarter-waves long can be substituted for the quarter-wave stub shown in *A*. In *B*, any shorted stub an odd number of quarter-waves long can be substituted. The impedance match to the line is made in the last quarter-wave section of the stub. Other arrangements also are possible, as explained previously.

(5) The stub-matching system has the disadvantage of limiting the frequency of operation, and the antenna must be near a resonant length to operate properly. This is especially true of the center-fed antenna, where the current loop presenting a low impedance can become a node presenting a high impedance. This must be borne in mind when determining what type of impedance-matching device is to be used.

h. Two-Wire Feed Using Q Match.

(1) In the stub-matching system, the line is connected to taps on the stub and the correct point at which to connect the line to obtain an impedance match is determined by trial-and-error methods. The *Q*-matching method eliminates the necessity for finding the correct impedance match by means of taps. The *Q*-matching device is an open quarter-wave section of line placed in series with the untuned transmission line. It has an input impedance matching the characteristic impedance of the line, and an output impedance matching the antenna input impedance.

(2) Since Z_o is the characteristic impedance of the line and Z_A is the terminal impedance of the antenna, then

$$Z_Q = \sqrt{Z_0 Z_A}$$

where Z_Q is the characteristic impedance of the line used for the matching section. For example, if a 600-ohm line is used to feed an antenna with input impedance of 70 ohms, then

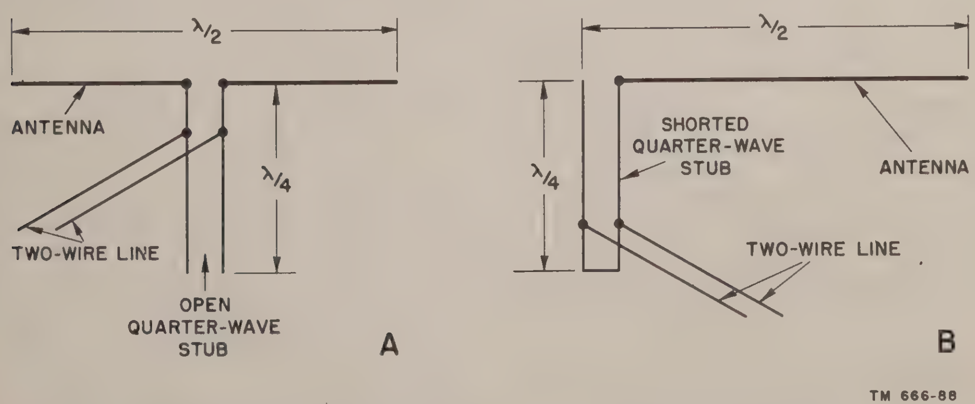


Figure 84. Matching with the shorted and open quarter-wave stubs.

$$Z_Q = \sqrt{(600)(70)}$$
$$= \sqrt{42{,}000}$$
$$= 205 \text{ ohms}$$

If a quarter-wave section of line having a characteristic impedance of 205 ohms is inserted between the transmission line and the antenna terminals, a perfect match results.

(3) The Q match is flexible in that any type of line can be used for the matching section, provided only that it has the characteristic impedance necessary. The quarter-wave matching section can have either air or solid dielectric. The Q match, however, loses its effectiveness rapidly as the frequency of operation swings away from the resonant frequency of the antenna. To lessen this effect, the impedances can be matched in *two* steps instead of one. This requires two quarter-wave sections.

(4) In the example given above, a 205-ohm quarter-wave section is used to match a 600-ohm line to a 70-ohm antenna impedance. In using two sections, an intermediate impedance is selected, and the first-section characteristic impedance found from the formula. For example, the first section matches the 600-ohm line to an impedance of 300 ohms. Then

$$Z_{Q1} = \sqrt{(600)(300)}$$
$$= \sqrt{180{,}000}$$
$$= 425 \text{ ohms}$$

The characteristic impedance of the first section is 425 ohms. Its input impedance is 600 ohms, and its output impedance is 300 ohms. The second quarter-wave

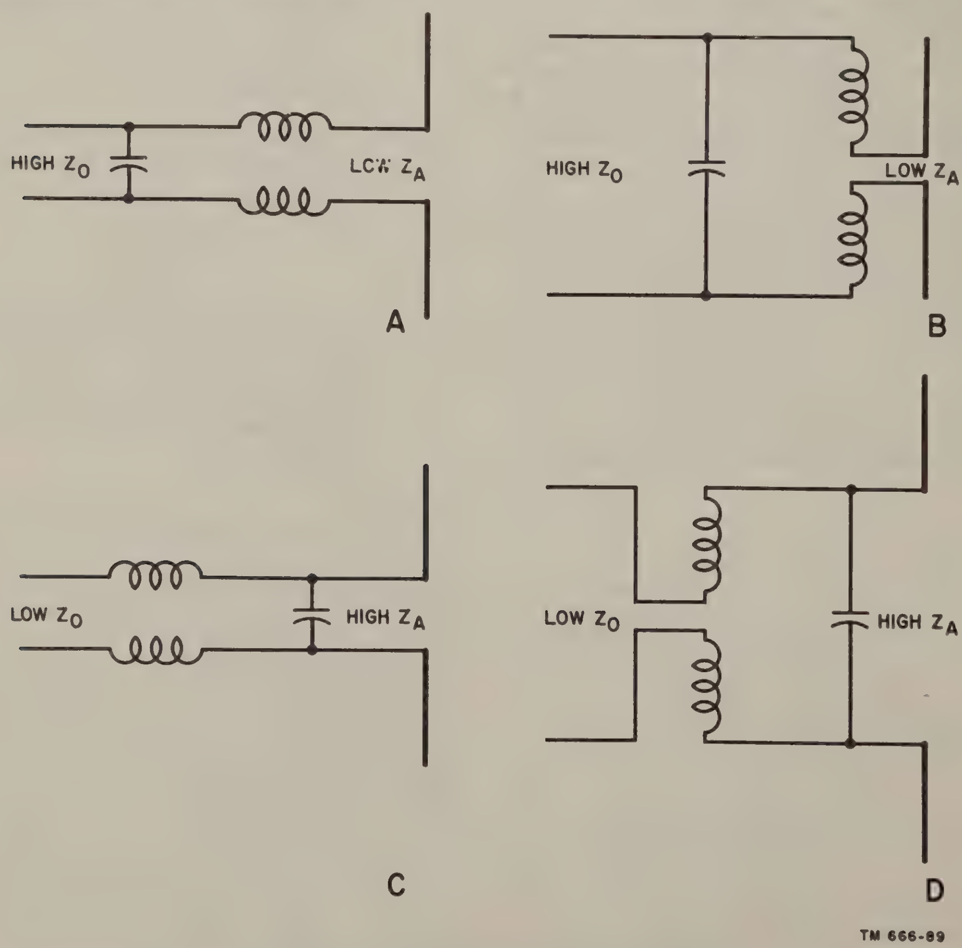


Figure 85. Artificial-line matching to antennas.

section then must have an input impedance of 300 ohms and an output impedance of 70 ohms. Its characteristic impedance therefore must be

$$Z_{Q2}=\sqrt{(300)(70)}$$
$$=\sqrt{21,000}$$
$$=145 \text{ ohms}$$

The second section then can be connected directly to the antenna terminals. As stated previously, there is no limitation on the type of line used to form the matching section.

i. Coaxial Line Feed. Coaxial cable using a solid dielectric can be constructed with a characteristic impedance equal to the input impedance of a center-fed antenna. This provides an extremely simple method of feed. The inner conductor is connected to one leg of the antenna, and the outer conductor to the other end. The line is unbalanced in this arrangement, and a bazooka section, therefore, is used to restore balance. If the coaxial cable is not a direct match for the antenna, stub matching can be used in the same manner as with the two-wire stubs. This is not practical, because the line must be tapped on the stub to obtain the correct impedance match. A simple method is to use a Q-matching section of coaxial line. Open coaxial lines also can be used to feed antennas. These are found in special transmitting applications. Usually, the line is filled with a gas dielectric and sealed to preserve a uniform impedance.

j. Artificial-Line Matching.

(1) Matching systems are used because a mismatch between the line and the antenna causes standing waves to appear on the line. This condition lowers the efficiency of energy transfer from the transmitter to the antenna. Thus far in this paragraph, the methods evolved for matching a nonresonant line to an antenna have involved transmission-line sections, such as stubs or quarter-wave transformers. Since transmission lines have distributed constants, it is possible to replace the distributed constants of the line section with the *lumped constants* of coils and capacitors to obtain impedance matches. Methods using lumped constants are classified under the heading of *artificial-line matching*.

(2) The chief advantage of the artificial line over the transmission-line section in impedance matching is the negligible amount of space occupied by lumped constants. Coils or capacitors in sealed weatherproof containers can be mounted right at the input terminals of the antenna. The main use of this type of line is at the lower frequencies, where equivalent transmission-line sections would have to be of excessive length.

(3) Several typical feed systems using artificial-line matching are shown in figure 85. In A and B, high impedance lines are used to feed a resonant antenna having low input impedance. The coil is divided equally between the two line conductors in order to maintain line balance. In C and D, the low-impedance line is used to feed a resonant antenna having high input impedance. The coils again are divided in order to preserve line balance, with the capacitor being placed across the line.

Section IV. BASIC RADIATION PATTERNS

52. Introduction

The first three sections in chapter 3 covered the various circuits necessary to transfer energy from the transmitter to the antenna. This energy is radiated from the antenna and forms a field having a definite pattern, depending on the type of antenna used. It is desirable, therefore, to be able to put the radiation pattern of an antenna on paper where it can be examined. In fact, the antenna usually is designed to have a specific pattern for use with a particular installation The radiation pattern is a measure of the energy radiated from an antenna taken at various angles and at a constant distance from the antenna.

53. Radiation Types and Patterns

a. General.

(1) A source of radiant energy such as the sun radiates light in all directions equally. A radiator of this type is known as an

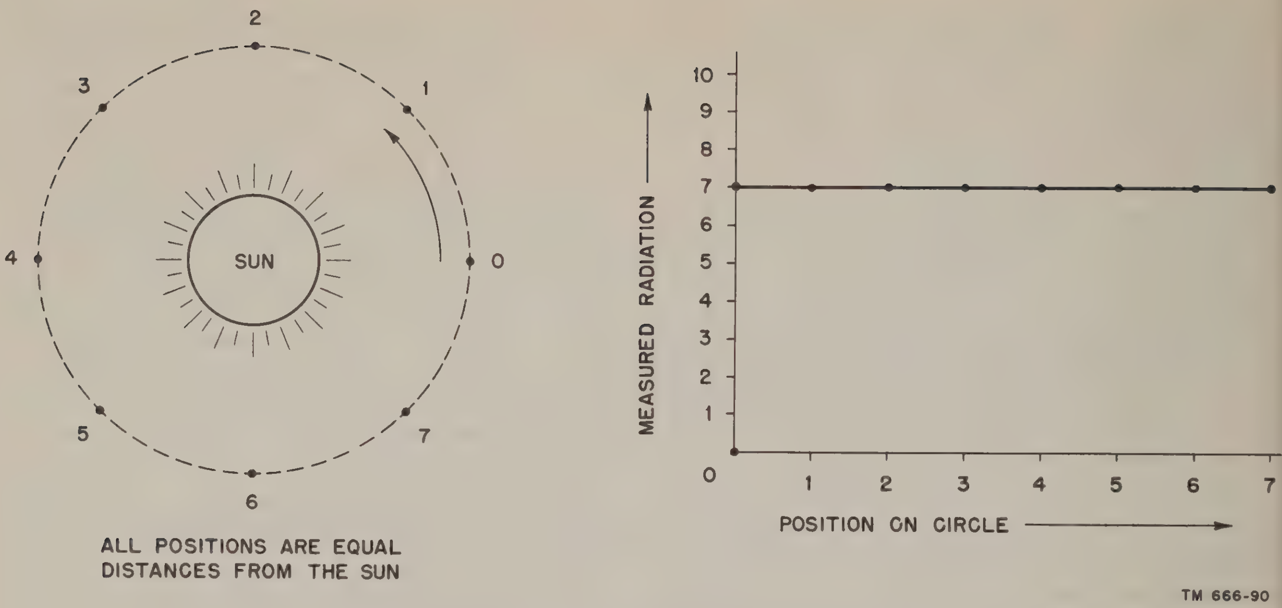


Figure 86. The sun as an isotropic source of radiation.

isotropic source of radiation. This simply means that the energy coming from the source is found to be constant at a fixed distance from whatever angle it is measured. Assume that a measuring device is moved in a circle around the sun. At any point along the circle, the distance from the measuring device to the sun is the same. The measured radiation also remains the same.

(2) If the measured radiation is plotted against various positions taken along the circle around the sun, the result is the graph in figure 86. Assume that the radiation is measured on a scale of 0 to 10 units, and that the radiation measured is shown to be seven units at each position. The graph of the measured radiation, therefore, is a straight line plotted against positions along the circle.

(3) The graph of measured radiation just described is a form of radiation pattern. The straight line represents the radiation pattern of an isotropic source taken in the plane of the measuring circle. It is possible to have a radiator which emits stronger radiation in one direction than in another. Such sources are called *anisotropic*. An example, shown in figure 87, is the ordinary flashlight. The beam illuminates only a portion of the total space surrounding the flashlight. If a

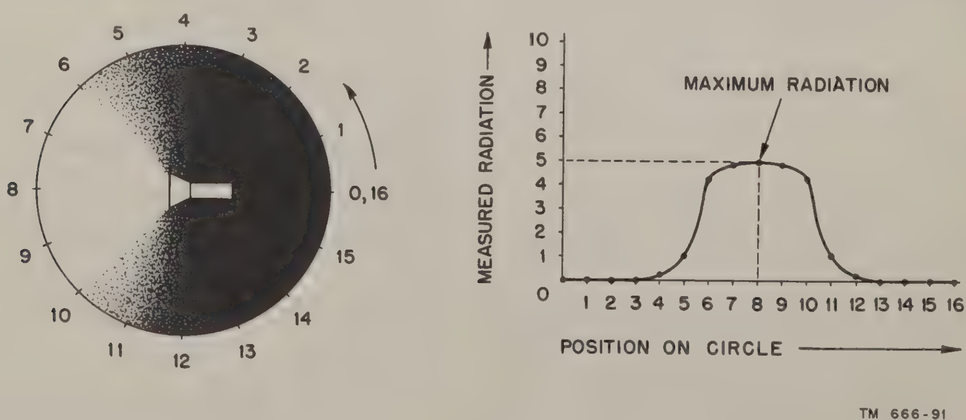


Figure 87. Flashlight as anisotropic source of radiation.

circle is drawn having the light source as center, the radiation can be measured at different positions along the circle. Each position used for measurement is the same distance from the light source. In other words, conditions are exactly those used in measuring the light radiated from the isotropic source.

(4) At position 0 on the circle, which is directly behind the light source, the radiation measured is negligible. A zero value accordingly is assigned to this position on the graph at the right. Until position 4 is reached, the radiation remains negligible. Between 4 and 6, the circle passes from comparative darkness into the flashlight beam. This is an area of sharp transition from darkness to brightness, as can be observed easily on the graph. Radiation is relatively constant moving from positions 6 to 10, reaching a maximum at position 8, which is directly in the path of the beam. Between 10 and 12, the measured radiation falls off sharply, becoming and remaining negligible from 13 to 16.

(5) Radiation from a light source and radiation from an antenna are both in the form of electromagnetic waves. The measurement of radiation from an antenna, therefore, follows the same basic procedure as the one just described for the sun and the flashlight. These measurements can be graphed to obtain a radiation pattern for the antenna. Before proceeding with the study of antenna patterns, however, it is desirable to understand in detail the various methods used to graph measured values of radiation.

b. Rectangular-Coordinate Pattern.

(1) In figures 86 and 87, the rectangular-coordinate type of graph is used to plot the measured value of radiation against the position at which the measurement is taken. For convenience, the graph of figure 86 is reproduced in *A* of figure 88. The numbered positions along the circle are laid out along the *horizontal* axis of the graph from 0 to 7. The units of measured radiation are laid out along the *vertical* axis from 0 to 10. Units on both axes usually are chosen so that the pattern occupies a convenient area of the graph.

(2) The horizontal and vertical axes are at right angles to each other. The point at which the axes cross each other is called the *origin*. In this case, the origin has the value of zero on both axes.

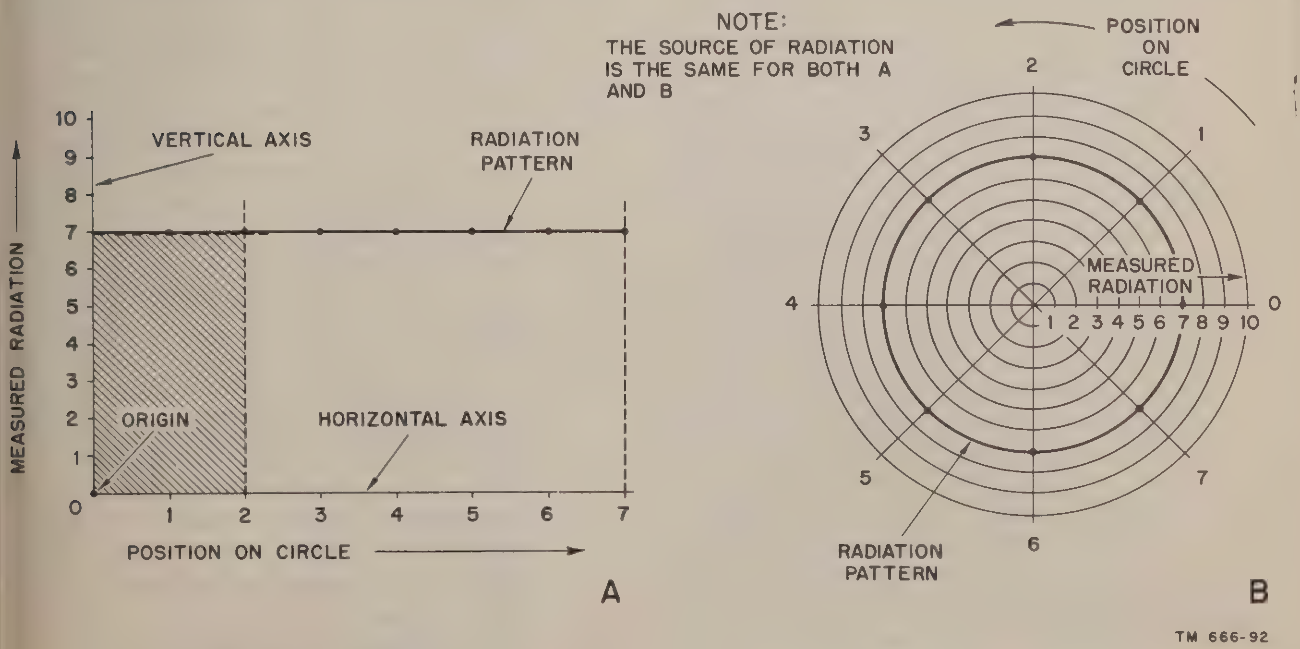


Figure 88. Comparison of rectangular-coordinate and polar-coordinate graphs for isotropic source.

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Now, assume that a radiation value of seven units is measured at position 2. From position 2 on the horizontal axis, a line (vertical dashes) is projected running parallel to the vertical axis. From 7 on the vertical scale, a line (horizontal dashes) is projected running parallel to the horizontal axis. The point at which the two lines intersect represents the value of seven radiation units at position 2. Note that this is the only point on the graph that can represent this value.

(3) The vertical and horizontal axes plus the two dashed lines used to plot the point inclose an area forming a rectangle (shaped area). It is for this reason that this type of graph is called a rectangular coordinate. A new rectangle is formed for each different point plotted. In the case given, all the points plotted lie along a straight line extending from seven units on the vertical scale to the projection of position 7 on the horizontal scale. The straight line, therefore, is the characteristic pattern in rectangular coordinates of an isotropic source of radiation.

c. *Polar-Coordinate Pattern.*

(1) Although the rectangular-coordinate method of graphical analysis is used widely, another method has proved to be of greater use in studying radiation patterns. This method is the *polar-coordinate* type of graphical analysis (B of fig. 88). Note the great difference in the shape of the radiation pattern when it is transferred from the rectangular-coordinate to the polar-coordinate graph. The scale of values used in both graphs is identical, and the measurements taken are both the same. The basic difference, which results in the difference in physical appearance, is in the type of axes used.

(2) In the rectangular-coordinate graph, points are located by means of projections from a pair of axes at right angles to each other. These axes remain stationary at all times. In the polar-coordinate graph, one axis consists of concentric circles, and the other axis consists of a rotating radius extending from the center of the concentric circles. Recall how radiation was measured by traveling in a circle around the sun. Assume a radius, R, drawn from the sun as center to position 0 on the circle. Moving to position 1, the radius moves to position 1; moving to position 2, the radius also moves to position 2; and so on. This moving radius constitutes the moving axis of the polar-coordinate graph.

(3) The positions of the radius are marked on the polar-coordinate graph for each position at which a measurement is taken. Note how the position of the radius indicates the *actual direction* from which the measurement was taken. This is a distinct advantage over the rectangular-coordinate system, in which the position is indicated along a straight-line axis having no physical relation to the position on the circle. Having established the direction in which the measurement was taken by means of the rotating axis, it remains to devise means for indicating the measured radiation.

(4) The rotating axis passes from the center of the graph to some position marked on the edge of the graph. In so doing, it intersects a set of concentric circles spaced at equal distances from each other. Going out from the center, the circles get larger and larger. These circles are used to indicate the measured radiation. They are numbered successively from the center outward, the center indicating a zero measurement. In the graph in *B* of figure 88, a radiation scale going from 0 to 10 units is used. Consequently, 10 concentric circles go from the center to the circumference of the graph. These circles are marked 1, 2, 3, and so on, with 10 designating the largest circle. This scale corresponds to the scale marked on the vertical axis of the rectangular-coordinate graph in *A*.

(5) Summing up, the rotating radius of the polar-coordinate graph serves the same purpose as the stationary horizontal axis of the rectangular-coordinate graph. It has the advantage of indicating the actual direction from which the measurement is taken. The concentric circles serve the same purpose as the verticle scale on the rectangular-coordinate graph. They allow the same scale to be used no matter

what the position of the rotating radius. The distance from the source is constant for both types of graphs.

(6) At position 0 in *B*, the radius extends from the center outward to the right. The radiation measured is seven units in this position. This point is recorded by going out seven circles along the radius. The point is the place where the radius intersects the seventh circle. The recording of the radiation measured in position 1 follows the same procedure. Since the source is isotropic, the measured radiation again is seven units. The radius is rotated to position 1, and its intersection with the seventh circle is marked.

(7) When all points are recorded through position 7, it is found that they all lie on the seventh concentric circle. The radiation pattern of the isotropic source, therefore, is a circle. This contrasts sharply with the straightline pattern obtained with a rectangular-coordinate-type graph. The advantages of the polar-coordinate graph are evident immediately. The source, which is at the center of the observation circle, is at the center of the graph. Also, the direction taken by the radiated energy can be seen directly from the graph. For these reasons, the polar-coordinate graph is more useful in plotting radiation patterns.

(8) In figure 87, the radiation pattern of the common flashlight was graphed in rectangular coordinates. This graph is reproduced for convenience in *A* of figure 89. From the physical picture of the flashlight beam, it is evident that the light source is anisotropic in nature. This is *not* evident in the radiation pattern traced on the rectangular-coordinate graph. Conversely, the radiation pattern of the flashlight shown in *B* of figure 89 bears some physical resemblance to the actual beam. This is the same pattern, drawn using polar coordinates.

(9) The positions on the circle marked off on the two polar-coordinate graphs given have been selected and numbered arbitrarily. It is possible to mark off positions around the circle in a standard way so that one radiation pattern can be compared easily with another. The standard method is based on the fact that a circle is divided into 360°. The radius extending from the center horizontally to the right (position 0 in *B* of fig. 89) is designated 0°. Advancing to position 4 rotates the radius until it is at right angles to the 0° radius. This radius position accordingly is marked 90°. Position 8

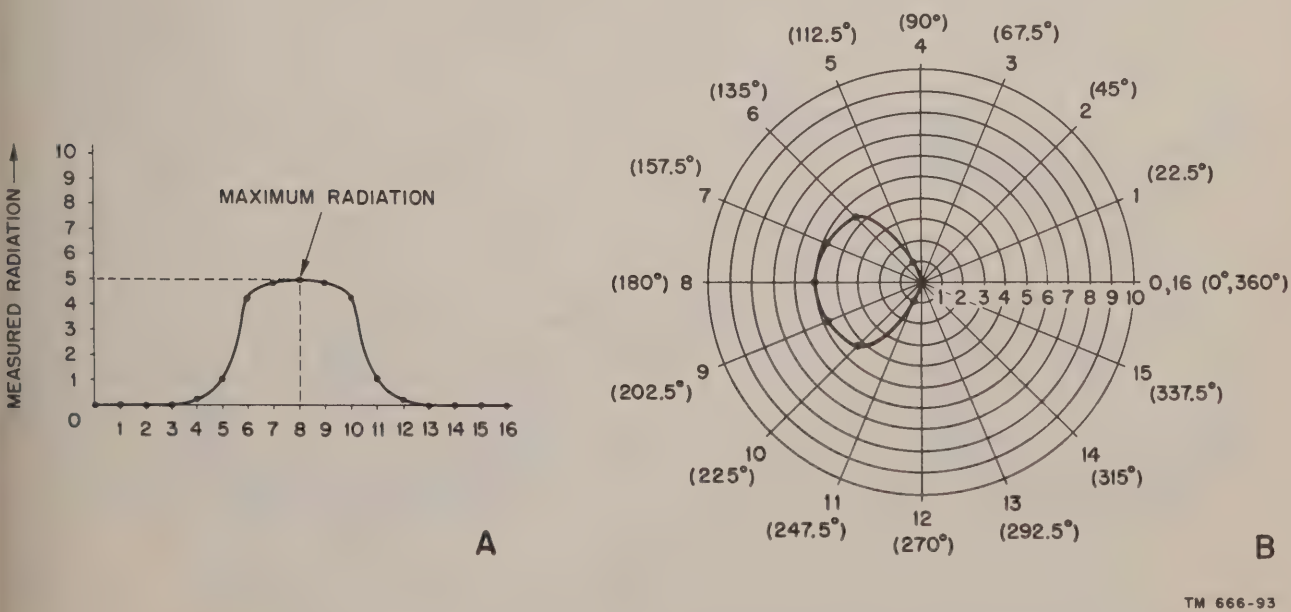

Figure 89. Comparison of rectangular-coordinate and polar-coordinate graphs for anisotropic source.

is, therefore, 180°, position 12 is 270°, and position 16 is 360°, by the same reasoning. The various radii drawn on the graph all are marked according to the angle each radius makes with the reference radius at 0°.

(10) In *B* of figure 89, the polar-coordinate graph shows a definite area inclosed by the radiation pattern, indicating the general direction of radiation from the source. This area is called a *lobe*. Outside of this area, no radiation is emitted in any direction. For example, at an angle of 45° (position 2), the radiation is zero. Such a point is called a *null*. Practically speaking, there is usually *some* radiation in every direction. A null, therefore, also is used to indicate directions of minimum radiation. In the pattern given, there is one lobe and one continuous null.

54. Dipole Antenna Radiation

a. Definitions. In the following discussion, the term *dipole* is used to mean the basic half-wave antenna. The term *doublet* is used to indicate an antenna that is very short compared with the wavelength of the operating frequency. Physically, it has the same shape as the dipole.

b. Radiation Pattern of a Doublet.

(1) The doublet is the simplest form of practical antenna. Since it is a source of radiation, its radiation can be measured and a radiation pattern plotted in the manner in which a flashlight and its beam were shown in figure 87. Figure 90 is a perspective view of the radiation

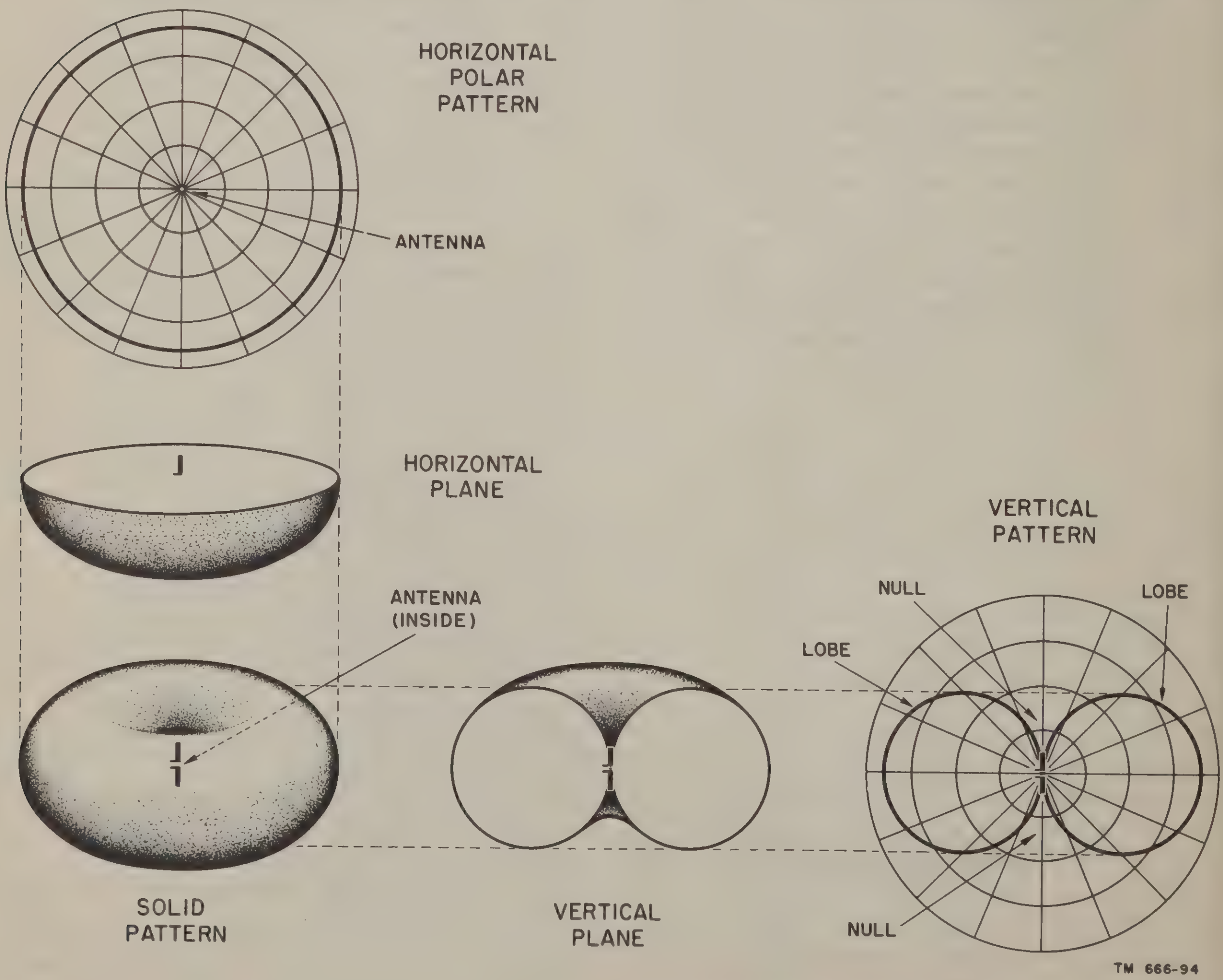

Figure 90. Development of vertical- and horizontal-plane polar patterns from solid radiation pattern.

pattern of a doublet. This is *not* a picture of the radiation, but a three-dimensional view of the pattern itself. In three dimensions, the pattern resembles a doughnut.

(2) From this perspective view, two types of polar-coordinate patterns can be drawn. The first is obtained by getting a top view of the doughnut in a horizontal plane through its center. This plane is the same as that of the circle drawn with dashes in the solid pattern. Looking down on the horizontal plane, the antenna axis is seen head on, so that it becomes simply a dot in the horizontal polar pattern. It can be seen from the horizontal pattern that the radiation is constant in any direction along the horizontal plane.

(3) A vertical plane view of the doughnut pattern can be drawn, from which is obtained a vertical polar pattern. To obtain this pattern, the doughnut is sliced in half along a vertical plane through the antenna. This can be seen in the figure to the right of the solid pattern. Note how the vertical plane view of the radiation pattern differs sharply from the horizontal plane view. The vertical pattern exhibits two lobes and two nulls. The difference in the vertical pattern is caused by the fact that no radiation is emitted from the ends of the doublet. Also, there is maximum radiation from the doublet in a direction perpendicular to the antenna axis. This type of radiation pattern is both *nondirectional* (in a horizontal plane) and *directional* (in a vertical plane).

(4) From a practical viewpoint, the antenna can be mounted vertically or horizontally. The doublet shown in figure 90 is mounted vertically, and the radiated energy spreads out about the antenna nondirectionally in the horizontal plane. Since this usually is the useful plane, this arrangement is termed nondirectional, and its directional characteristic in other

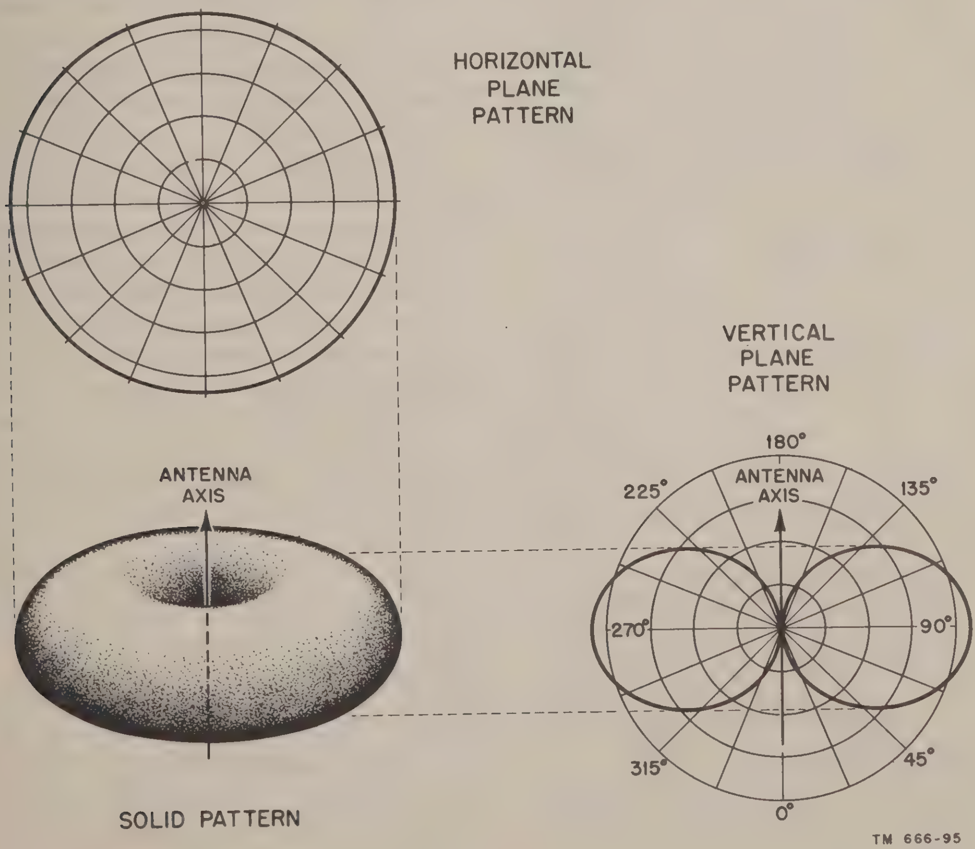

Figure 91. Radiation pattern of dipole (half-wave) antenna.

planes is ignored. If the doublet is mounted horizontally, it has the effect of turning the pattern on edge, reversing the patterns given in figure 90. The antenna is now directional in the horizontal plane. The terms nondirectional, directional, and so on are used for convenience in describing specific radiation patterns. A complete description always involves a figure in three dimensions, as in the solid pattern of figure 90.

c. Radiation Pattern of a Dipole. The radiation pattern of a dipole is similar to that of the doublet. Increasing the length of the doublet until it is a half-wavelength has the effect of flattening out the doughnut pattern (fig. 91), or forming a flattened figure 8. The radiation pattern in the horizontal plane is a larger circle than in the doublet. The vertical radiation-pattern lobes no longer are circular. They are flattened out, and the radiation intensity is relatively greater. The elongation of the pattern is greatest perpendicular to the antenna axis. On the vertical radiation pattern, 0° is used to indicate a position off one end of the antenna. All angular measurements around the graph are made from this point. A position at right angles to the source of radiation accordingly is designated 90° or 270°. A position off the opposite end of the antenna is marked 180°, and so on. This method of starting at one end of the antenna axis is conventional.

55. Using Radiation Pattern

a. Antennas usually are constructed to obtain a specific radiation pattern. Actual tests then are conducted to discover whether the practical antenna radiation pattern conforms to the pattern desired. Field tests of this type usually are carried out by measuring the relative field strength of the antenna in terms of microvolts per meter. This measurement utilizes the E field of the antenna. Since power is directly proportional to the square of voltage ($P=E^2/R$), the measurements obtained can be used to plot a radiation pattern. This is the simplest and most common method for taking measurements of antenna field strength. Measurements involving actual power require elaborate equipment.

b. Since two types of pattern can be obtained, the voltage measurements can be used to plot a field-strength pattern, or can be squared to plot a power pattern. These patterns indicate *relative* field strength and *relative* power. In practice, there is little difference between the patterns, and both are used. Relative field-strength and relative power patterns for the same source of radiation are illustrated in figure 92. Maximum radiation is taken to be 1, and radiation in every other direction is expressed in terms of fractions of the maximum.

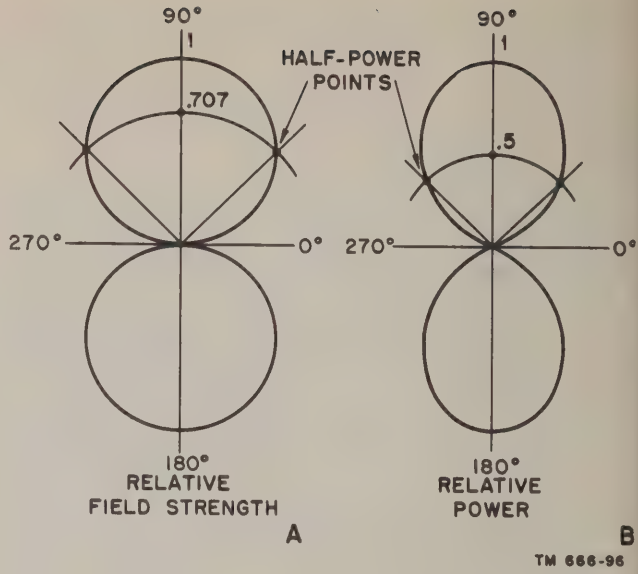

Figure 92. Beam width measured on relative field strength and relative power patterns.

c. Although the radiation pattern consists of areas inclosed by curves, it must be remembered that the actual radiation streams out from the source for great distances. The radiation takes the general directions indicated by the radiation-pattern lobes. There is little or no radiation in the directions indicated by nulls. For convenience in indicating the general direction of radiation, the term *beam width* is used. The radiation beam is considered to leave the antenna between the points where the field strength falls off to 0.707 of maximum, or where the power falls off to 0.5 of maximum.

d. In A of figure 92, the field strength is maximum at 90° and 180°. There are nulls at 0° and 270°. Between each null and maximum, the field strength rises from zero to one. The angles at which the voltage is 0.707 are marked in the figure. The beam is assumed to be contained within the total angle from 0.707 through a maximum to 0.707. This total angle is the *beam width.* In this case, the beam is 90° wide, as indicated in the figure.

e. The field strength pattern in *A* is related

directly to the power pattern in B. This is because the power is directly proportional to the square of the voltage. The same points can be found on the power pattern by taking the square of the voltage values used to determine the beam width.

$$P_r :: E_r^2$$
$$:: (0.707)^2$$
$$:: .5$$

where P_r is the relative power and E_r is the relative voltage. The beam width on the relative power pattern, therefore, is found by locating the half-power points. The beam width in B is also 90°. In other words, the beam width is constant, whichever type of graph is used.

f. When looking at the plane patterns in figure 92, bear in mind that they are cross sections of solid radiation patterns. Although there are two lobes in the plane radiation pattern, there is only one lobe in the solid pattern, and only one beam. It is possible to have more than one beam, as will be shown in chapter 4.

Section V. PRACTICAL HALF-WAVE ANTENNAS

56. Introduction

a. The half-wave antenna has been discussed previously without reference to the effect produced by the presence of ground on the radiation pattern. Since all practical antennas are erected over the earth and not out in free space, it is necessary to determine just what effect the ground produces. The presence of ground may alter completely the radiation pattern produced by the antenna, and ground also will have an effect on some of the electrical characteristics of the antenna.

b. In general, the ground has the greatest effect on those antennas which must be mounted fairly close to it in terms of wavelength. For example, medium- and high-frequency antennas elevated above ground by only a fraction of a wavelength will have radiation patterns that are quite different from the free-space patterns.

c. In addition to ground effects, several examples of practical half-wave antennas are discussed in this section. These include the conventional single-wire, half-wave dipole, the folded dipole, the coaxial antenna, and the conical antenna.

57. Ground Effects

a. Assume that a horizontal half-wave antenna is erected at a vertical distance, H, from a ground plane, as illustrated in figure 93, where B is the end view. Some of the energy that leaves the antenna travels directly to some distant point, P. This energy is referred to as the direct wave in the figure. The direction followed by the direct wave makes a certain angle, A, in respect to the horizontal.

b. Some of the energy leaving the antenna travels downward toward the ground plane. Since this ground plane is a good conductor, the downward traveling wave from the horizontal antenna is reflected with practically no loss and a reflected wave of energy travels outward toward the distant point, P. The angle between the reflected wave and the perpendicular is exactly equal to the angle between the downward traveling wave from the antenna and the perpendicular.

c. During the actual reflection process, a 180° phase shift takes place so that the reflected wave is 180° out of phase with the direct wave. The highly conducting ground plane then cannot sustain the horizontal lines of electric force produced by the antennas. In order to produce zero voltage along the ground, an electric field is assumed to be produced that is equal in amplitude but opposite in direction to that produced by the antenna. If a vertical antenna is used, the electric field is vertical. Under these conditions, no phase reversal takes place during the actual reflection.

d. Regardless of whether a phase shift is produced, the distant point, P, is acted on by two waves. One of these waves is the direct wave and the other is the reflected wave. The reflected wave travels a greater distance than does the direct wave. Therefore, there is an additional phase shift so far as the reflected wave is concerned, because of the greater distance it must travel. For example, if the reflected wave travels a distance to point P that is a half-wavelength longer than the distance traveled by the direct wave, an additional 180° phase shift will result from the greater path length.

e. The signal strength at point P depends on the amplitudes and phase relations of the direct and reflected waves. If the ground is a good conductor so that very little absorption of energy occurs during the reflection process, the reflected wave has the same amplitude as the direct wave.

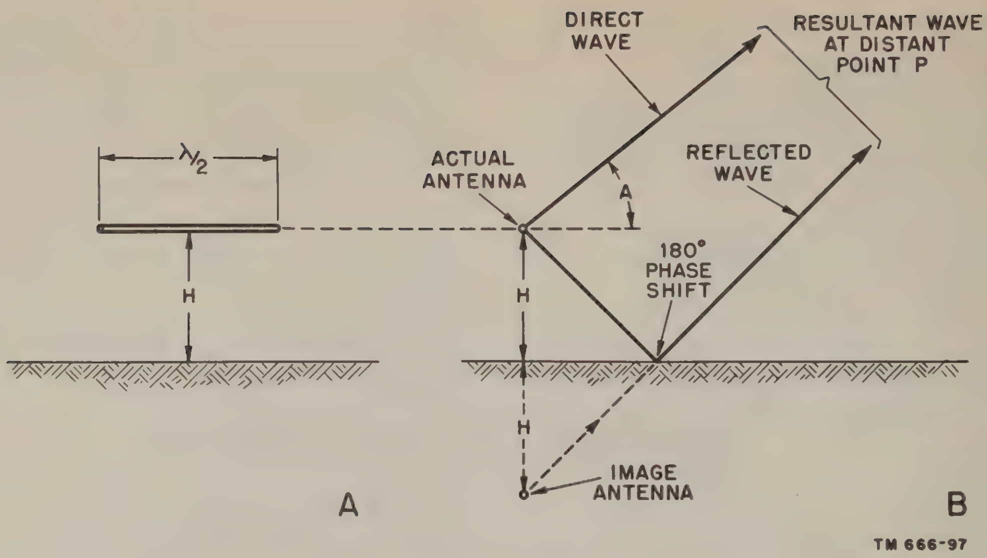

Figure 93. Reflection produced by ground plane.

If these two equal-amplitude waves arrive at the distant point in phase, the resultant signal strength is twice that of the direct wave alone. On the other hand, if these waves arrive 180° out of phase, the resultant signal strength is zero. Intermediate values of signal strength occur with intermediate phase relations between the reflected and the direct wave.

f. Assume that point P is so located that it receives twice the signal strength. Now assume that a second point, Q, is located slightly below point P. The distances to point Q might be such that the direct and reflected waves arrive 180° out of phase. As a result, cancelation occurs, the received signal strength is zero, and a null is produced. Because of ground reflections, then, it is possible that the radiation pattern may be broken up into a series of lobes. The signal strength at the center of the lobes will be about twice that which would be received if the antenna were not in the vicinity of a ground plane. These lobes are separated by nulls where the received signal strength is zero.

g. It is sometimes convenient in making calculations to use the idea of an *image antenna.* This is an imaginary antenna assumed to be located the same distance, H, below ground as the actual antenna is located above ground. The reflected wave is assumed to come from the image antenna, as shown in B of figure 93. When a horizontal antenna is used, to take into account the phase reversal that takes place when reflection occurs, the current in the image antenna is assumed to be 180° out of phase with the current in the actual antenna. When a vertical antenna is used, the current in the image antenna is considered to flow in the same direction the current flows in the actual antenna.

58. Ground-Affected Radiation Patterns

a. Reflection Factor.

(1) The reflection factor is a term by which the free-space radiation pattern of an antenna must be multiplied in order to determine the radiated field strength of a practical antenna at a given vertical angle. The maximum value of the reflection factor is 2. At those vertical angles, the direct and reflected waves are in phase, and twice the free-space signal strength occurs. The minimum value of the reflection factor is 0. At those vertical angles, the direct and reflected waves are of opposite phase, and complete cancelation occurs. The reflection factor then may vary from 0 to 2 at vertical angles measured above the plane of the ground. Reflection factors are not given for angles below the surface of the earth.

(2) The value of the reflection factor depends on the height of the antenna above the ground plane as well as the orientation. The following chart gives the value of the factor for horizontal half-wave anten-

nas at various vertical angles when the antenna is located a *quarter-wavelength above ground:*

Vertical angle (degrees)	Reflection factor	Vertical angle (degrees)	Reflection factor
0	0	50	1. 8
10	. 5	60	1. 95
20	1. 0	70	2. 0
30	1. 5	80	2. 0
40	1. 75	90	2. 0

(3) When the horizontal antenna is located a *half-wavelength above ground*, the following chart can be used to obtain the reflection factor:

Vertical angle (degrees)	Reflection factor	Vertical angle (degrees)	Reflection factor
0	0	50	1. 4
10	1. 0	60	. 75
20	1. 75	70	. 4
30	2. 0	80	. 1
40	1. 75	90	0

(4) When the horizontal antenna is located *3 quarter-wavelengths above ground*, the following chart is used to obtain the reflection factor:

Vertical angle (degrees)	Reflection factor	Vertical angle (degrees)	Reflection factor
0	0	50	1.
10	1. 5	60	1. 7
20	2. 0	70	1. 9
30	1. 5	80	2. 0
40	0	90	2. 0

(5) When a height of *1 wavelength above ground* is used, the following chart shows the reflection factor:

Vertical angle (degrees)	Reflection factor	Vertical angle (degrees)	Reflection factor
0	0	50	1. 95
10	1. 8	60	1. 4
20	1. 6	70	. 6
30	0	80	. 1
40	1. 6	90	0

(6) These charts also can be used with a half-wave vertical antenna. The height above ground is measured from the center of the vertical antenna. It is necessary, however, to subtract the given values of reflection factor from 2. Then, if the reflection factor given in the charts for a certain height and vertical angle is 1, the reflection factor for a vertical antenna is 2 minus 1, or 1. If the reflection factor for the horizontal antenna is 2, the factor for the vertical half-wave antenna is 2 minus 2, or 0. If the reflection factor for the horizontal antenna is 0, then the vertical antenna reflection factor is 2 minus 0, or 2.

b. Horizontal Half-Wave Antenna.

(1) When the foregoing reflection factors are applied to the free-space radiation pattern of a horizontal half-wave antenna, the patterns shown in figure 94 are produced. Patterns *A*, *C*, *E*, and *G* are the vertical radiation patterns in the plane of the antenna itself. *B*, *D*, *F*, and *H* are the vertical radiation patterns in the plane which is at right angles to the antenna. Patterns *A* and *B* are for antenna heights of a quarter-wavelength; *C* and *D* are for antenna heights of a half-wavelength; *E* and *F* are for heights of 3 quarter-wavelengths; *G* and *H* are for heights of 1 wavelength.

(2) Figure 95 permits a better visualization of the radiation pattern produced. Here the actual solid radiation pattern is shown for a horizontal half-wave antenna located a half-wavelength above ground. In the vertical plane at right angles to the antenna, *D* of figure 94 shows two large lobes the maximum values of which occur at an angle of 30° with the horizontal. This pattern is reproduced in perspective at the upper left of figure 95. In the vertical plane which included the antenna, reference to *C* of figure 94, shows two small lobes with maximum values occurring at an angle of about 40° with the horizontal. This pattern is reproduced in perspective at the upper right of figure 95. If these two plane views are connected smoothly, the solid pattern shown in the center of figure 95 is produced.

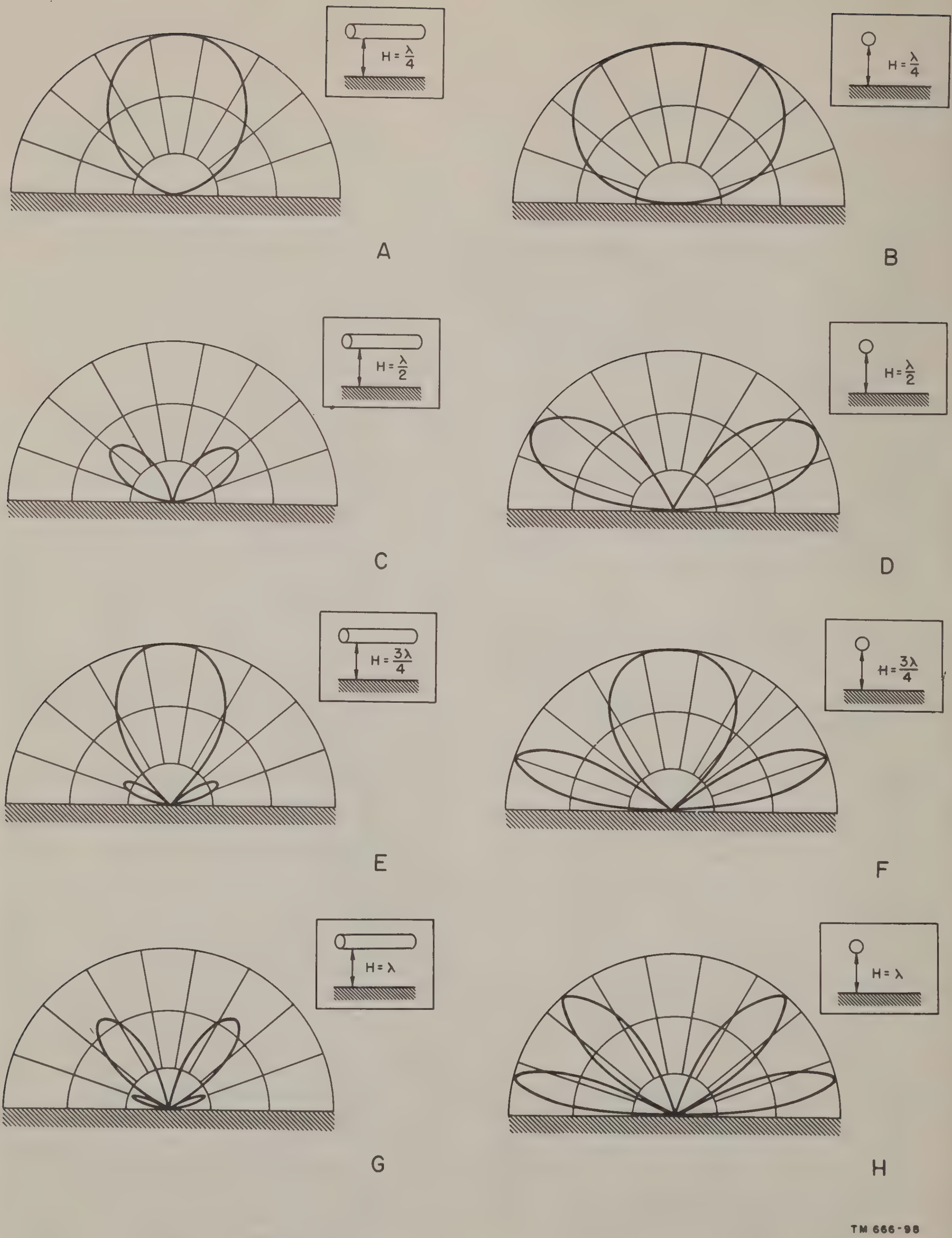

Figure 94. Vertical-plane radiation patterns of horizontal half-wave antennas.

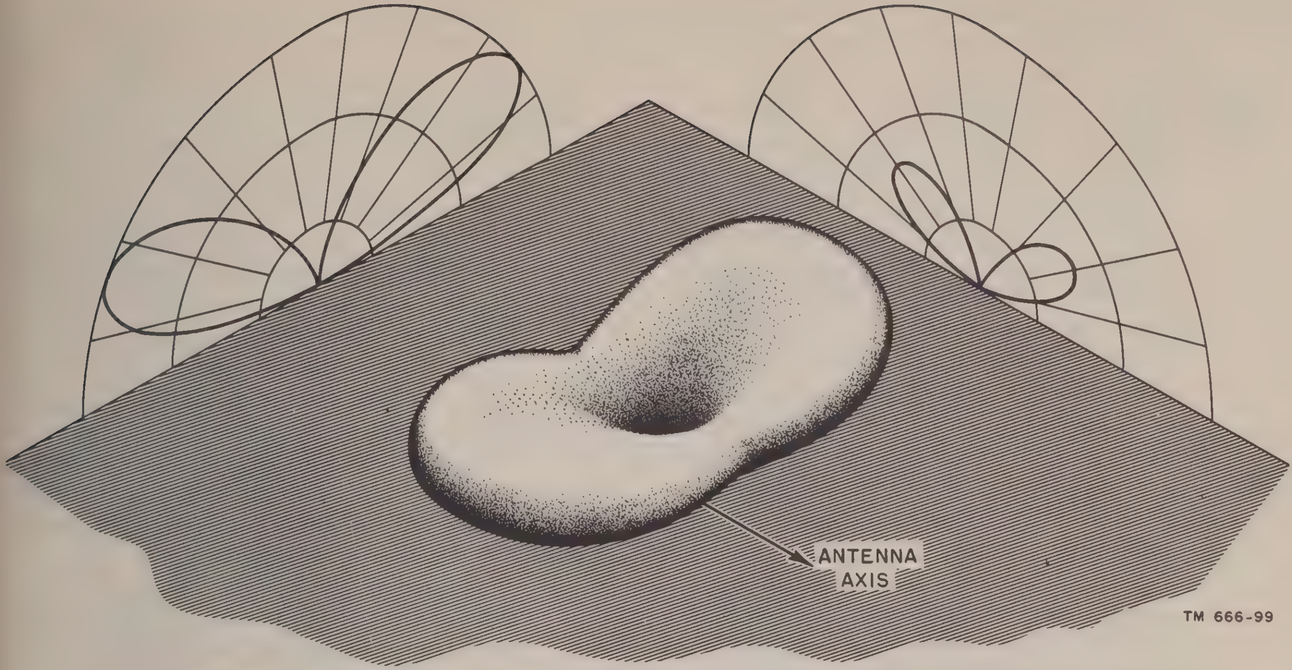

Figure 95. Solid pattern produced by horizontal half-wave antenna located a half-wavelength above ground.

(3) In a similar manner, solid radiation patterns can be visualized from the plane views shown in figure 94. Picture the pattern as being produced by the smooth transition from one vertical plane view shown to the other vertical plane view shown as an angle of 90° is covered.

(4) Although vertical patterns are shown for only four specific heights above ground, it is not too difficult to predict the patterns produced at intermediate heights. This is true since the patterns do not change abruptly as the height of the antenna is increased gradually. Instead, there must be a smooth transition from the pattern shown for a height of a quarter-wavelength, to the pattern shown for a height of a half-wavelength.

(5) At heights less than a quarter-wavelength above ground, the vertical patterns produced by a horizontal half-wave antenna are almost perfectly circular. As the antenna is raised, the vertical pattern is flattened somewhat at its top, at a vertical angle of 90° (*B* of fig. 94). As the height is increased above a quarter-wavelength, a depression begins to appear at the top of the pattern, and the pattern width increases. The depression grows deeper and deeper as the antenna height approaches a half-wavelength. Finally, at a height of a half-wavelength, the pattern splits into two separate lobes. The radiation at a vertical angle of 90° (straight up) is zero at this height, as in *D* of figure 94. As the antenna height increases still more, a lobe of radiation begins to grow out of the center of the pattern at a vertical angle of 90°. As this lobe increases in amplitude with increasing antenna height, the two side lobes are spread farther apart so that their maxima occur at lower vertical angles. This vertical lobe has its maximum amplitude and begins to flatten somewhat (*F* of fig. 94) at an antenna height of 3 quarter-wavelengths. As the antenna height is increased still more, the vertical lobe develops a depression that grows deeper as the height is increased. Finally, at a height of 1 wavelength, the center lobe splits into two separate lobes and the radiation at a vertical angle of 90° is again zero. Now four distinct lobes exist (*H* of fig. 94).

(6) The patterns that are produced at antenna heights in excess of 1 wavelength also can be determined by studying figure 94. When the height of the horizontal antenna is an odd number of quarter-wave-

lengths above ground, a lobe of maximum radiation is produced at a vertical angle of 90° straight up.

(7) Consider an antenna with a height of 1 quarter-wavelength above ground. Assume that the instantaneous electric field immediately around the antenna is maximum in a given direction, designated as *positive.* A portion of this field moves downward a distance of a quarter-wavelength to the ground. Upon being reflected, a 180° phase shift occurs, and the instantaneous electric field is now maximum in the opposite direction, designated as negative. This negative field now moves upward from the ground for a distance of a quarter-wavelength. By the time the reflected field returns to the antenna, a total distance of a half-wavelength has been covered. Meanwhile, since one-half cycle of operation has elapsed during the time required for the downgoing wave to move from the antenna to the ground and from the ground back to the antenna again, the polarity of the energy on the antenna itself has reversed. As a result, the reflected wave arrives back at the antenna in exactly the right phase to reinforce the direct wave. The reinforcement occurs not only at heights of a quarter-wavelength above ground, but also at heights of 3 quarter-wavelengths, 5 quarter-wavelengths, 7 quarter-wavelengths, and so on. Consequently, a lobe of maximum radiation is produced at a 90° vertical angle for all antenna heights which are an odd number of quarter-wavelengths from ground.

(8) When the height of the antenna is an even number of quarter-wavelengths above ground, a null (zero radiated energy) occurs at the 90° vertical angle. Consider the action of the horizontal half-wave antenna that is located at a distance of a half-wavelength above ground. The portion of the radiated field from this antenna which travels downward toward the ground must cover a total distance of 1 wavelength before it arrives back at the antenna. The direction of this field is reversed by the reflection process. During the time that is required for the reflected wave to cover this distance, the field immediately surrounding the antenna has gone through 1 complete cycle and is now back to its original direction or polarity. The reflected wave, therefore, with its field reversed by the reflection process, becomes 180° out of phase with the direct wave from the antenna. As a result, cancelation occurs at the vertical angle of 90°, and a null is produced. This cancelation, as described above, occurs not only at heights of a half-wavelength above ground, but also at heights of 1 wavelength, 1½ wavelengths, and so on. Consequently, null is produced at a 90° vertical angle for all antenna heights which are an even number of quarter-wavelengths from ground.

(9) One other factor can be observed from the patterns in figure 94 which can be used to determine the vertical radiation pattern of a horizontal half-wave antenna at heights greater than are shown. At a height of 1 quarter-wavelength above ground, the radiation pattern is seen to consist of one lobe only. At a height of 2 quarter-wavelengths ($\lambda/2$) above ground, the radiation pattern consists of two lobes. At a height of 3 quarter-wavelengths, the pattern consists of three lobes. At a height of 4 quarter-wavelengths (λ) above ground, the radiation pattern consists of four lobes. Consequently, the number of vertical lobes produced is numerically equal to the height of the antenna above ground in quarter-wavelengths and continues for any antenna height. It is possible to get a fairly good idea of the vertical radiation pattern of a horizontal half-wave antenna at any height above ground. For example, if the antenna is located at a height of 2 wavelengths above ground, which is an even number of quarter-waves, a null is produced at a vertical angle of 90°. Then, since 2 wavelengths represent 8 quarter-wavelengths, the radiation pattern consists of eight lobes.

c. Vertical Half-Wave Antenna.

(1) When the proper reflection factors are applied to the free-space radiation pattern of a vertical half-wave antenna, the

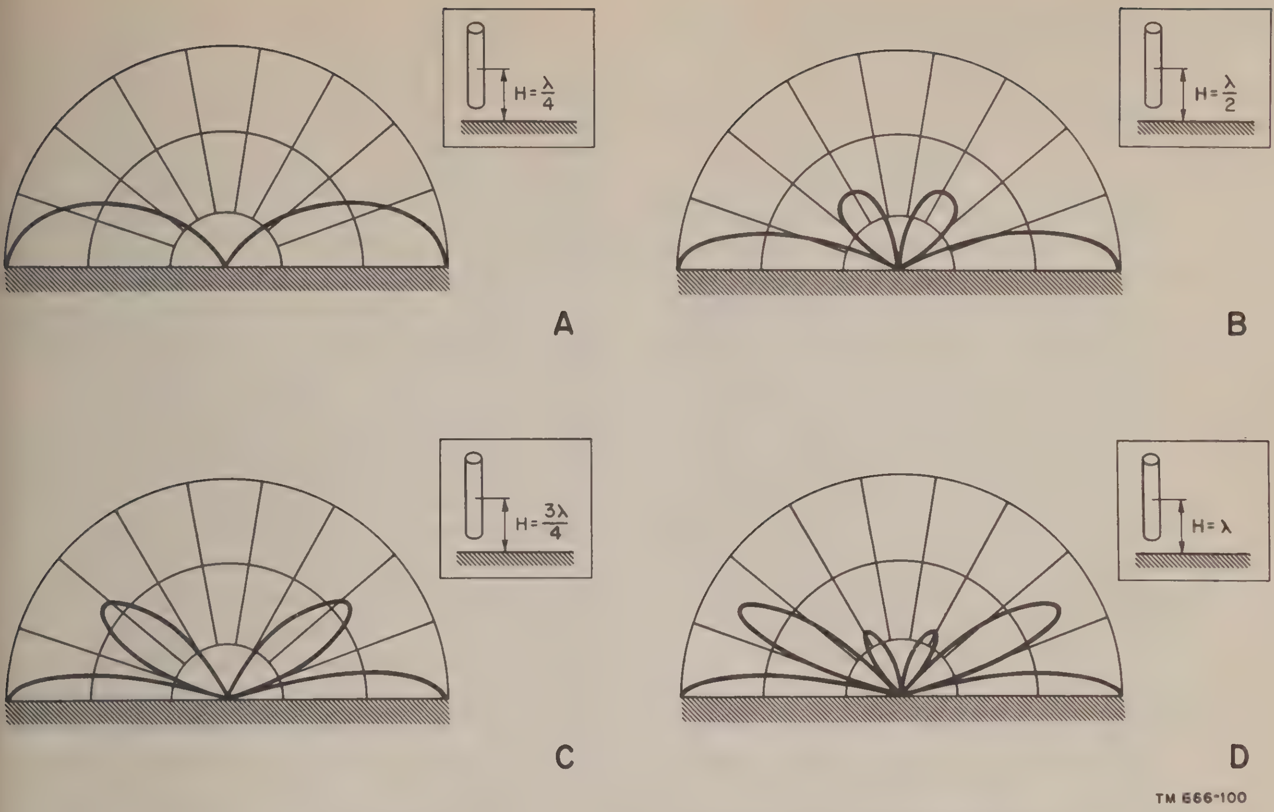

Figure 96. Vertical-plane radiation patterns produced by vertical half-wave antennas.

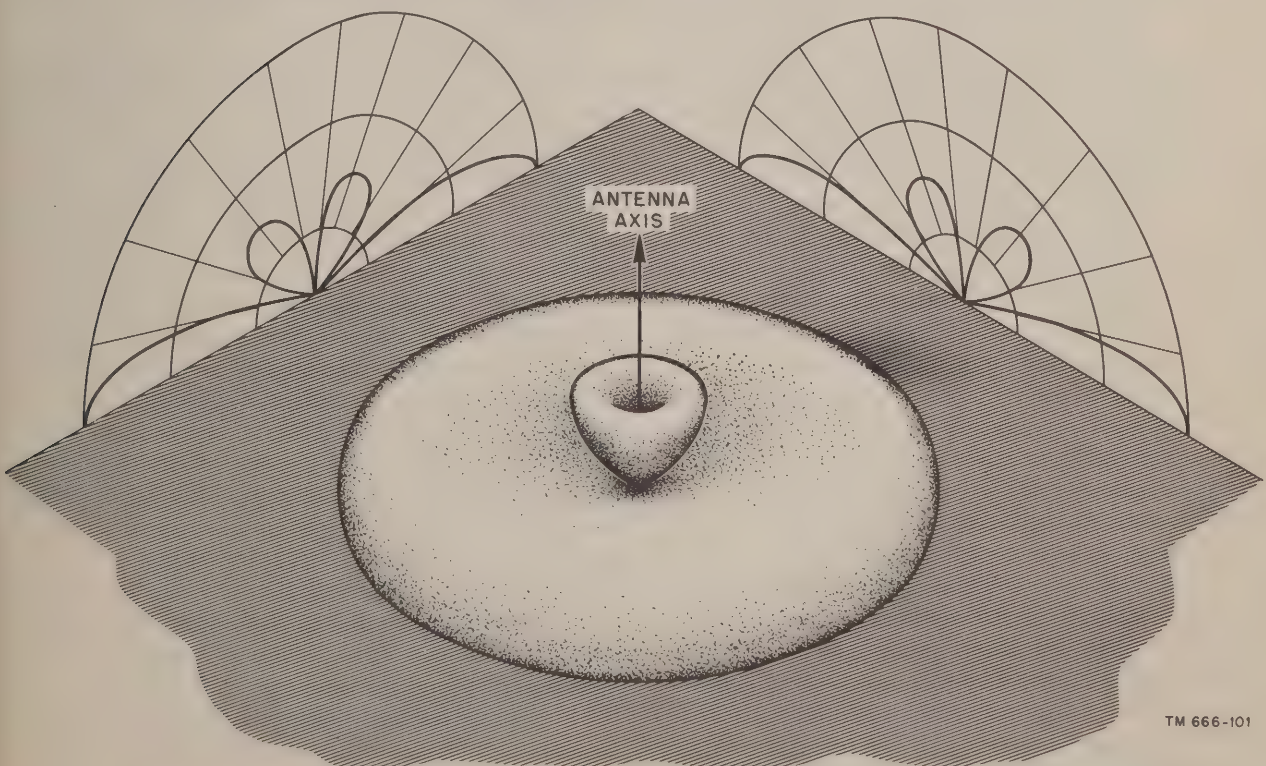

Figure 97. Solid pattern produced by vertical half-wave antenna located a half-wavelength above ground.

patterns shown in figure 96 are produced. Only a simple plane view need be shown here because the vertical half-wave antenna is nondirectional in the horizontal plane. Its free-space horizontal radiation pattern is a circle. Therefore, the effect of the reflection factor is the same in all horizontal directions.

(2) To visualize more clearly the solid radiation pattern, it is necessary only to picture the plane patterns shown in figure 96 being rotated. One such solid radiation pattern is shown in figure 97, where the pattern is produced by a vertical half-wave antenna the center of which is a half-wavelength above ground.

(3) In general, two effects are shown when the patterns of figure 96 are observed. First, there is always a null at the vertical angle of 90° because there is no radiation from the end of the vertical antenna. Therefore, regardless of the value of the reflection factor at this angle, no radiation occurs directly upward. At all antenna heights, then, the vertical half-wave antenna produces a null at 90°. The second effect noted is that, as the antenna is raised above ground, a greater number of lobes appear in the pattern. At a height of 1 quarter-wavelength, for example, two lobes appear (*A* of fig. 96). When the antenna is raised to 1 half-wavelength, four lobes appear, as in *B*. The amplitude of the upper lobes is much smaller than that of the lobes which lie along the ground. At a height of 3 quarter-wavelengths, there are still four lobes, but the amplitude of the upper lobes has increased, as shown in *C*. When the antenna is raised to a height of a full wavelength, as in *D*, six lobes appear.

59. Changes in Radiation Resistance

a. The radiation resistance measured at the center of a half-wave antenna in free space is 73 ohms. However, the radiation resistance of a practical half-wave antenna located over a ground plane may have any value of radiation resistance from 0 to almost 100 ohms. The exact value of radiation resistance depends on the height of the antenna above ground.

b. The change in radiation resistance occurs because of the effect of the wave reflected up from the ground plane. This reflected wave induces a voltage which causes a current to flow in the antenna. The phase of this induced current in respect to the current in the antenna produced by the transmitter depends on the height of the antenna and its orientation. At some antenna heights, it is possible for the two currents to be in phase so that the total antenna current is greater than it would be if no ground reflection had taken place. At other antenna heights, the two currents may be 180° out of phase so that the total antenna current is less than it would be if no ground reflection had occurred. Intermediate antenna heights result in induced currents having different phase relations. Therefore, the total antenna current varies widely, depending on the antenna height.

c. If a given input power is applied to an antenna and the antenna current increases, the antenna behaves as though its resistance were reduced. Since the ohmic resistance of the antenna does not change, the radiation resistance is lowered effectively. Similarly, if the antenna height is such that the total antenna current decreases, the antenna radiation resistance is increased.

d. The actual variation in radiation resistance of a half-wave antenna at various heights above ground is shown in the graph in figure 98. The solid curve shows the radiation resistance of a horizontal half-wave antenna, and the dashed curve shows the radiation resistance of a vertical half-wave antenna. The radiation resistance of the horizontal antenna rises steadily to a maximum value of 98 ohms at a height of about 3 eighths-wavelengths. Then the radiation resistance falls steadily to 58 ohms at a height of about 5 eighths-wavelengths. The resistance then continues to rise and fall around an average value of 73 ohms, which is the free-space value. As the height is increased, the amount of variation keeps decreasing. The curve is similar to a damped oscillation.

e. The variation in radiation resistance of a vertical antenna is much less than that of the horizontal antenna. The radiation resistance is a maximum value of 100 ohms when the center of the antenna is a quarter-wavelength above ground. The value falls steadily to a minimum value of 70 ohms at a height of a half-wavelength above ground. The value then rises and falls by several

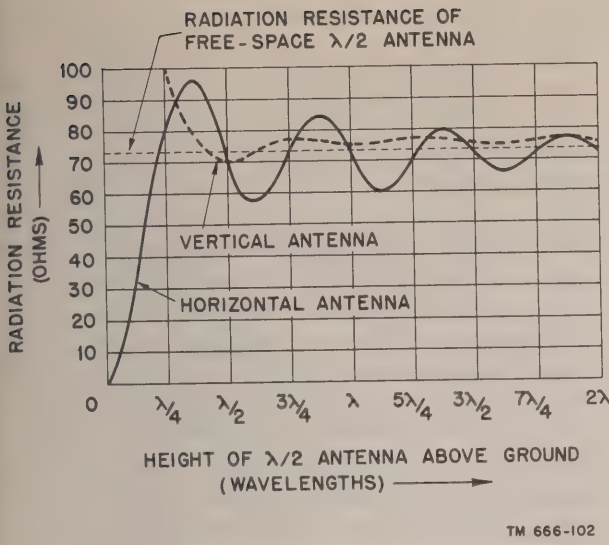

Figure 98. Radiation resistance at various heights.

ohms about an average value slightly above the free-space value of a horizontal half-wave antenna.

f. Because of the variation in antenna current and radiation resistance at various antenna heights, the field intensity produced by a given antenna also changes. In general, as the radiation resistance is reduced, the field intensity increases. An increase in radiation resistance results in a drop in the radiated field intensity.

60. Effects of Practical Grounds

a. General.

(1) Up to this point, all of the effects produced have been the result of a ground which has a uniform high conductivity. In practice, the nature of the ground over which the antenna is erected is subject to considerable variation. This results not only from the ground material itself but also the manner in which it is found. For example, the antenna may be erected over a ground which has high or low conductivity, and over a ground with uniform or nonuniform conductivity in the vicinity of the antenna. All of these characteristics of the ground have an effect on the radiation patterns and resistance of the antenna.

(2) Table VI gives the approximate relative conductivities of various surfaces that may be found under an antenna. Note the wide variation in conductivity that occurs. It is not strange then that a considerable variation in ground effects occurs over different types of surfaces.

Table VI. Ground Material Conductivity.

Ground material	Relative conductivity
Sea water	4, 500
Flat, rich soil	15
Average flat soil	7
Fresh water lakes	6
Rocky hills	2
Dry, sandy, flat soil	2
City residential area	2
City industrial area	1

b. Ground Losses.

(1) Unless the ground behaves as a nearly perfect conductor, the amplitude of the ground-reflected wave will be much less than the amplitude of the wave before reflection. A portion of the wave which ordinarily would be reflected is absorbed by the resistance of the ground. Such absorption by the ground constitutes *ground losses.* This means that the value of the ground reflection factor will be reduced considerably.

(2) The maximum value of the ground reflection factor is 2 (par. 58*a*(1)). At those values of vertical angle at which the factor is 2, the total signal strength (resulting from the direct and ground-reflected waves) is *twice* the value of the direct wave alone. If the ground is a poor conductor, the maximum value of the ground reflection factor is much less than 2. As a result, the maximum value of the lobes never rises to twice the value without ground reflections. In addition, no nulls are produced over an imperfect ground. To produce a null, the ground-reflected wave must be 180° out of phase with the direct wave and must be of *equal amplitude.* As a result, complete cancelation occurs and a null results. If the ground is imperfect, some of the wave that would be reflected is absorbed instead. Ground losses occur, and the amplitude of the ground-reflected wave is reduced. Consequently, complete cancelation cannot occur at a given vertical angle.

Therefore, instead of an actual null being produced, a reduction in resultant signal strength occurs.

(3) The value of ground reflection factor over a perfectly conducting ground (that is, one with no ground losses) varies from 0 to 2. Nulls are produced at those values of vertical angle where the factor is 0, and lobes of double signal strength occur where the factor is 2. Over a moderately conducting ground, the factor may increase to a maximum value of only 1.5 and may drop to a minimum value of 0.5. As a result, the vertical radiation pattern shows a series of high and low signal strengths rather than a series of double-amplitude lobes separated by well defined nulls. When the ground acts as a very poor conductor, practically all of the energy directed down toward the ground is absorbed and ground reflections do not occur. The ground reflection factor is then 1 over a wide range of vertical angles, resulting in a free-space pattern.

c. Frequency Effects.

(1) From the preceding discussion of the effects of imperfect grounds and from the relatively low conductivities of all surfaces (table VI), it would appear that the entire previous discussion concerning ground effects is not too important. However, such is *not* the case.

(2) At low and medium frequencies, the radio wave that strikes the ground causes ground currents to flow which penetrate the ground to a depth of 50 feet or more. In general, a greater penetration occurs when the top layer of ground has a low conductivity. Consequently, even though the actual conductivity of the soil itself may not be great, the volume of soil in which current can flow is considerable. As a result, the resistance of the ground is low, and, for all practical purposes, most types of soil act as rather good reflectors. Only a relatively small amount of ground loss occurs and the ground reflection factors vary from 0 to 2. The vertical radiation patterns shown previously in this chapter then apply almost exactly when low and medium frequencies are used.

(3) At higher frequencies (3 to 30 mc), the depth of penetration of a radio wave into the earth is limited to about 5 to 10 feet. Unless the antenna is erected over salt water or over a very highly conducting soil, considerable ground losses occur and much absorption of radiated energy occurs at vertical angles less than about 10° to 12°. At very low vertical angles (approximately 1° to 3°) so much absorption occurs because of ground losses that the ground reflection factor is reduced to a very low value, and the vertical-plane radiation patterns shown in figure 96 must be modified to take this factor into account. These patterns should show little or no radiated field intensity at very low vertical angles. The large lobe of radiation which lies along the ground plane then is reduced in amplitude, and a null is produced along the ground.

d. Radiation Resistance Effects.

(1) The graph in figure 98 shows the variation in radiation resistance for half-wave antennas at various heights above ground. The curves in this figure have been plotted for antennas erected above a highly conducting ground. If an imperfectly conducting ground is used, the curves shown must be modified.

(2) In general, the use of an imperfectly conducting ground shifts the curves shown slightly toward the left. In addition, the curves do not rise to as high values nor do they fall to as low values as when a highly conducting ground is used. The effect is to smooth out the curves and reduce the amount of change in radiation resistance as the antenna height is increased above ground.

e. Antenna Height.

(1) It is not possible always to answer accurately the question of what determines the exact height of a given antenna above ground. It might be assumed that it is necessary simply to measure the distance between the antenna itself and the surface of the ground. This method, however, may not give accurate results so far as reflection factors and vertical-plane pat-

terns are concerned. Instead, several feet must be added to the actual measured height. It is just as though ground reflections take place from a plane located a few feet below the surface of the ground.

(2) If the ground were a perfect conductor, no penetration of the radio wave would occur. Under these conditions, reflection takes place at the surface of the ground, and the *actual* height above ground can be used. In an imperfectly conducting ground, reflection seems to occur from a plane that is located below the surface and the actual depth of the reflecting plane is determined largely by the nature of the ground and the frequency used. This depth may be considerably greater than the few feet mentioned above. Since it is difficult to determine the actual depth of the ground reflecting plane, the exact effect on the radiation patterns and resistance of the antenna cannot be determined precisely, but sufficiently accurate results are obtained for all practical purposes.

61. Ground Screens

a. A ground screen consists of a fairly large area of metal mesh or screen which is laid on the surface of the ground under the antenna. Special mesh made of copper, Copperweld, or galvanized iron is available in large sheets for this purpose. Ordinary chicken wire also can be used although it will introduce some losses. When sheets of mesh are used, they must be bonded together at several places to keep the over-all resistance of the ground screen low. Although a ground screen simply can be laid on the surface of the ground, lower losses occur if it is connected to the earth by means of ground rods. The rods are driven into the earth to a depth of 4 to 8 feet. The metal screen then is bonded to the rods. Sometimes a ground screen is laid on a wooden framework that is erected 8 to 12 feet off the ground. The metal mesh usually is stapled to the framework; the grounding wires are run from the mesh to ground rods.

b. The purpose of the ground screen is to simulate to some extent the effect of a perfectly conducting ground under the antenna. The screen should extend for a considerable distance in every direction from the antenna. In practice, however, the ground screen seldom extends more than a half-wavelength or slightly less in all directions.

c. Two specific advantages are to be gained when a ground screen is used. First, the ground screen reduces ground absorption losses which would occur when the antenna is erected over imperfectly conducting ground. Second, by using the ground screen, the height of the antenna above ground is set accurately. As a result, the radiation resistance of the antenna is known and the radiation patterns of the antenna can be predicted more accurately.

d. For the ground screen to have any effect on the very low-angle radiation produced by the antenna, it would have to be unreasonably large, since ground reflections that effect such radiation take place at a considerable distance from the antenna. When a ground screen is used which extends for only a half-wavelength in every direction from the antenna, only the high-angle radiation is affected. The ground reflections that contribute to such radiation take place rather close to the antenna itself. Therefore, the ground screen is effective in such cases.

62. Polarization

a. General.

(1) Polarization of a radiated wave is determined by the direction of the lines of force making up the electric field. If the lines of electric force are at right angles to the surface of the earth, the wave is said to be vertically polarized. If the lines of electric force are parallel to the surface of the earth, the wave is said to be horizontally polarized.

(2) When a single-wire antenna is used to extract energy from a passing radio wave, maximum pickup results if the antenna is so oriented that it lies in the same direction as the electric-field component. Thus, a vertical antenna is used for efficient reception of vertically polarized waves and a horizontal antenna is used for the reception of horizontally polarized waves. In some cases, the orientation of the electric field does not remain constant. Instead, the field rotates as the wave travels through space. Under these conditions, both horizontal and vertical components of the field exist and the wave is said to have elliptical polarization.

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(3) When a half-wave antenna is used for the radiation of energy, the electric lines of force are built up from one end of the antenna to the other. At a distance from the antenna, the lines of force have a direction that is parallel to the direction of the radiating antenna. Therefore, the horizontal half-wave antenna produces a horizontally polarized radio wave and the vertical half-wave antenna produces a vertically polarized radio wave.

b. Polarization Requirements for Various Frequencies.

(1) At medium and low frequencies, groundwave transmission is used widely, and it is necessary to use vertical polarization. The lines of electric force are perpendicular to the ground and the radio wave can travel a considerable distance along the ground surface with a minimum amount of attenuation. Horizontal polarization cannot be used since, under these conditions, the electric lines that touch the earth do so parallel to it. Because the earth acts as a fairly good conductor at these low frequencies, the horizontal lines of electric force are shorted out, and little useful range can be covered with horizontal polarization.

(2) At high frequencies, with sky-wave transmission, it makes little difference whether horizontal or vertical polarization is used. The sky wave that has been reflected by the ionosphere arrives at the receiving antenna elliptically polarized. This is the result of the effect of the earth's magnetic field on a wave traveling obliquely through it and striking the ionosphere. The radio wave is given a twisting motion and its orientation changes continually because of the unstable nature of the ionosphere. The relative amplitudes and phase difference between the horizontal and vertical components of the received wave change at random, and the transmitting and receiving antennas therefore can be mounted either horizontally or vertically.

(3) One reason for the preference for horizontally polarized antennas in the high-frequency range is that less interference is experienced because of man-made noise source. Vehicular ignition systems, various rotating machinery, and many electrical appliances produce vertically polarized interference signals. The response to these signals is minimized by using horizontal polarization. Supports for horizontally polarized antennas are of more convenient size. There also is less absorption of radiated energy by building or wiring when horizontal polarization is used.

(4) With frequencies in the very-high or ultra-high range, either horizontal or vertical polarization is satisfactory. The radio wave travels directly from transmitting antenna to receiving antenna and the ionosphere is not used. The original polarization produced at the transmitting antenna is maintained throughout the entire travel of the wave to the receiver. Therefore, if a horizontal half-wave antenna is used for transmitting, a horizontal antenna must be used for receiving. If a vertical half-wave antenna is used for transmitting, a vertical antenna must be used for receiving.

(5) In some cases, the orientation of the receiving antenna need not be the same as the transmitting antenna for vhf and uhf signals. For example, when duct transmission occurs, as described in chapter 2, the orientation of the wave may change as the energy travels to the receiving antenna in much the same way as when a high-frequency sky wave is reflected from the ionosphere. Similar antenna orientations are not required when a large amount of the received energy arrives at the receiving antenna through diffraction or by reflection from irregular surfaces or from large flat oblique surfaces—for example, when the receiving antenna is located in an urban area near large buildings. Since duct transmission is an abnormal condition and most military vhf and uhf antennas are located in the clear away from large reflecting surfaces, the same antenna orientation generally is used for the receiving antenna as for the transmitting antenna.

c. Advantages of Vertical Polarization.

(1) Simple, vertical, half-wave antennas can be used to provide omnidirectional (in

all directions) communication. This is advantageous when it is desired to communicate with a moving vehicle.

(2) When antenna heights are limited to 10 feet or less over land, as in a vehicular installation, vertical polarization results in a stronger received signal at frequencies up to about 50 mc. From approximately 50 to 100 mc, there is only a slight improvement over horizontal polarization with antennas at the same height. Above 100 mc, the difference in signal strength is negligible. One polarization may produce a greater or smaller signal strength, depending on local conditions.

(3) For transmission over sea water, vertical polarization is decidedly better than horizontal when antennas are below approximately 300 feet at 30 mc, but only 50 feet at 85 mc, and still lower at the higher frequencies. Therefore, at ordinary antenna mast heights of 40 feet, vertical polarization is advantageous for frequencies less than about 100 mc.

(4) Radiation using vertical polarization is somewhat less affected by reflections from aircraft flying over the transmission path. With horizontal polarization, such reflections cause variations in received signal strength. This factor is important in locations where aircraft traffic is heavy.

(5) When vertical polarization is used, less interference is produced or picked up because of strong vhf and uhf broadcast transmission and reception (television and f-m (frequency-modulation)), all of which use horizontal polarization. This factor is important when an antenna must be located in an urban area having several television and f-m broadcast stations.

d. Advantages of Horizontal Polarization.

(1) A simple horizontal half-wave antenna is bidirectional. This characteristic is useful if it is desired to minimize interference from certain directions.

(2) Horizontal antennas are less apt to pick up man-made interference, which ordinarily is polarized vertically.

(3) When antennas are located near dense forests, horizontally polarized waves suffer lower losses than vertically polarized waves, especially above about 100 mc.

(4) Small changes in antenna location do not cause large variations in the field intensity of horizontally polarized waves when antennas are located among trees or buildings. When vertical polarization is used, a change of only a few feet in the antenna location may have a considerable effect on the received signal strength. This is the result of interference patterns which produce standing waves in space when spurious reflections from trees or buildings occur.

(5) Since the interference patterns will vary even when the frequency is changed by only a small amount, considerable distortion may occur when complex types of modulation are used, as with television signals or with certain types of pulse-modulation systems. Under these conditions, horizontal polarization is preferred.

(6) When simple half-wave antennas are used, the transmission line, usually vertical, is less affected by a horizontally mounted antenna. By keeping the antenna at right angles to the transmission line and using horizontal polarization, the line is kept out of the direct field of the antenna. As a result, the radiation pattern and electrical characteristics of the antenna are practically unaffected by the presence of the vertical transmission line.

63. Reciprocity

a. The half-wave antenna has the property of reciprocity since, when it is used for transmitting, it has the same characteristics as when used for receiving.

b. The function of a transmitting antenna is to convert the output power delivered by a radio transmitter into an electromagnetic field that is radiated through space. As such, the transmitting antenna is a *transducer* which converts energy having one form to energy having another form. The receiving antenna is also a transducer; however, it makes the energy conversion in the opposite direction. The function of the receiving antenna is to convert the electromagnetic field that sweeps by it into energy that is delivered to a radio receiver. In transmission, the antenna operates as the load for the transmitter; in recep-

tion, it operates as the power source for the receiver, which is the load.

c. A half-wave antenna used for transmitting radiates its maximum energy at right angles to the antenna itself and no energy is radiated in the direction of the antenna elements. When such an antenna is used for reception, it receives maximum energy at right angles to the antenna and no energy is received in the direction of the antenna elements. A vertically mounted half-wave antenna radiates energy equally in all horizontal directions. A similar antenna used for reception receives energy equally in all horizontal directions. Consequently, a pattern which shows the radiation of an antenna can be used also to show the reception of that antenna. A radial line drawn at a given angle from the center of such a pattern to its edge not only can be used to indicate the magnitude of the radiated field traveling outward on the pattern from the antenna but also shows the magnitude of the received field traveling inward on the pattern toward the antenna.

d. This reciprocity of radiation and reception applies not only to the half-wave antenna but also to more complicated antennas and arrays described later in this manual. In all cases, if an antenna is highly directive as a transmitting antenna, it will have exactly the same directivity as a receiving antenna.

e. The gain of an antenna is the same regardless of whether the antenna is used for transmitting or for receiving (par. 82). The impedance and the distribution of standing waves of voltage and current are identical regardless of whether the half-wave antenna is used for transmitting or for receiving.

f. If the reciprocity of an antenna is to be realized fully, it is necessary that the nature of the wave remain unchanged as it travels from transmitting antenna to receiving antenna. If it does not, two identical antennas similarly oriented may not act as though their characteristics were truly reciprocal. For example, assume that two such antennas, *A* and *B*, are used for communication by way of the ionosphere. When antenna *A* is transmitting to antenna *B*, the radiated energy follows a certain path up toward the ionosphere and then down toward antenna *B*. When antenna *B* is transmitting to antenna *A*, it is possible that a slightly different path is followed by the radiated energy in travelling toward antenna *A*. Under these conditions, the received wave at *A* will arrive at a slightly different vertical angle, and a different part of the directive pattern will be used.

g. For complete reciprocity to exist, it is necessary that antennas be terminated similarly when transmitting and receiving. If proper impedance matching is used when an antenna is transmitting, a proper match must exist also when the antenna is used for receiving. If it does not, the antenna will have somewhat different characteristics when it is used for transmission than when it is used for reception.

64. Single-wire Antenna

a. General.

(1) A single-wire, half-wave antenna is one constructed of a single conductor of proper length. In the high-frequency range, the conductor is usually a stranded copper-alloy wire which is suspended between two upright supports. In the vhf and uhf frequency ranges, aluminum tubing frequently is used, and the antenna length is sufficiently short that the tubing need be supported only at the center.

(2) The single-wire antenna can be mounted either vertically to produce a vertically polarized radio wave, or horizontally, to produce a horizontally polarized wave. Any of the feeding methods previously described can be used, depending on the type of transmission line or the nature of the output circuit of the transmitter that is to be connected to the antenna. Most of the figures so far in this manual show single-wire, half-wave antennas. Details of erection and construction have been omitted since only the theory of the antenna operation was under discussion.

b. Typical Military Antennas.

(1) The typical military half-wave antenna in figure 99 is suitable for transmission and reception. It can be used in conjunction with a transmitter having an output power of less than 100 watts. All of the component parts required for the installation are furnished in kit form. When the antenna is disassembled, it is highly portable.

(2) Sufficient antenna wire is provided to construct a half-wave antenna resonant

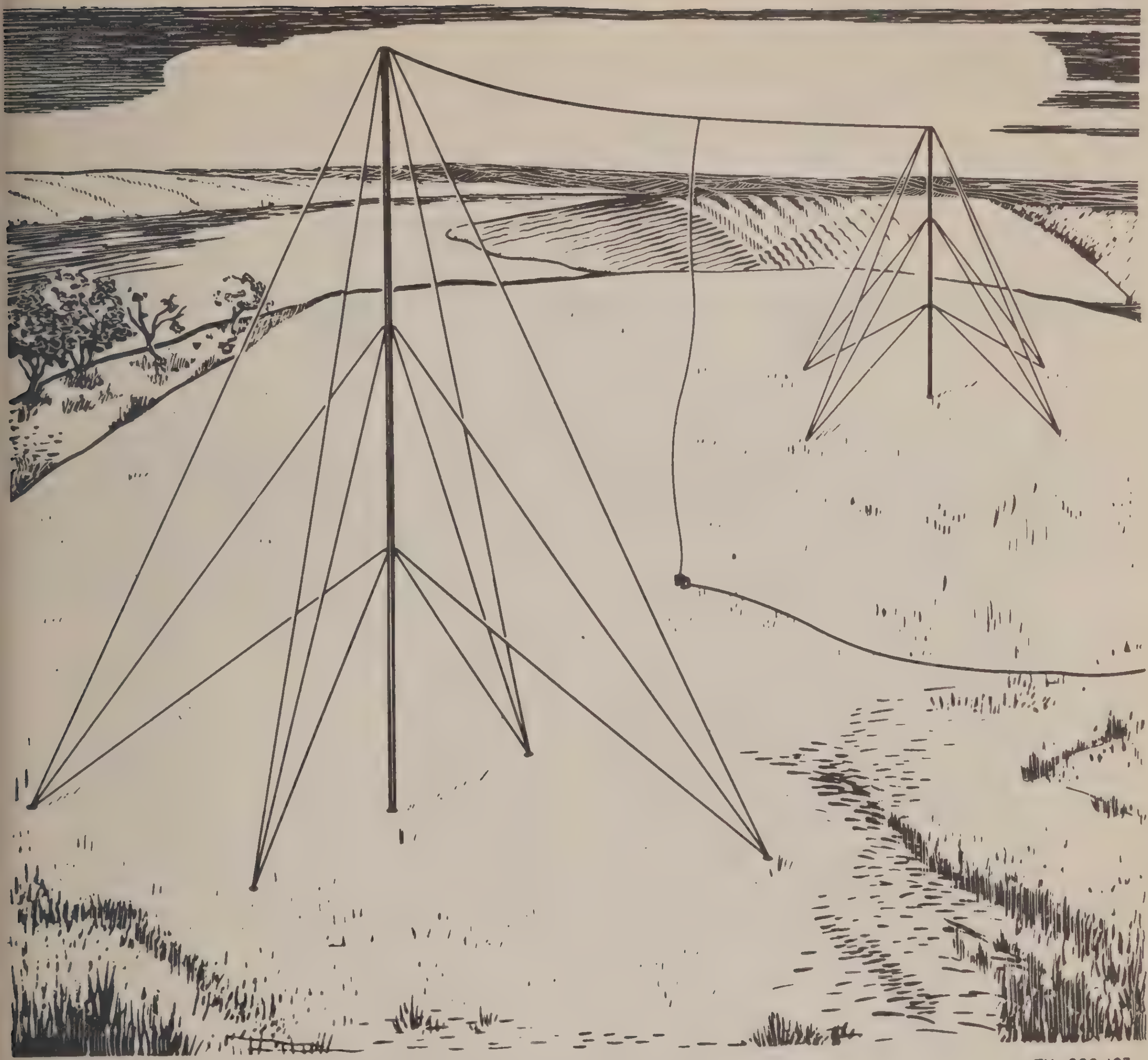

Figure 99. Typical military single-wire antenna.

to a frequency as low as 1.5 mc, that is 312 feet long. If the antenna is to operate on a frequency as high as 18 mc, the length is shortened to 24.3 feet. In actual practice, antenna wire forming one-half of the antenna is wound on a small reel. The wire is unwound from the reel until one-half the required antenna length is obtained. Then the free end of the wire is attached to an insulator at the center of the antenna. The reel then is attached to a halyard which has a strain insulator in it. The halyard is passed through a pulley at the top of one of the antenna supports with the free end made fast to a guy stake on the ground. Both halves of the antenna are made up in this way. The insulator at the center of the antenna is fitted with a female coaxial fitting. This accommodates a 72-ohm coaxial line which leads to either the transmitter or the receiver, providing the correct impedance for matching to the center of the half-wave antenna.

(3) A single-wire transmission line also can

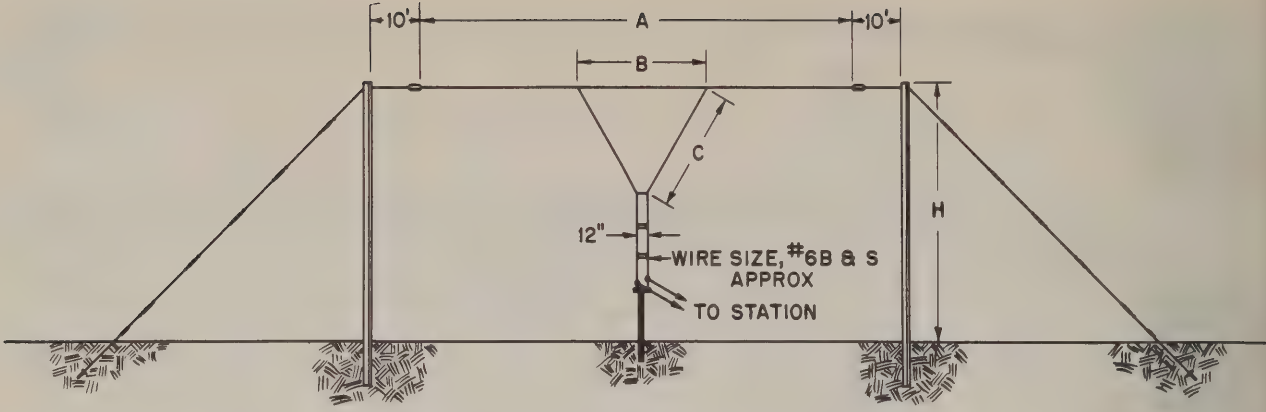

Figure 100. Delta-matched military antenna.

be used with this antenna. Here, the center insulator is not used and the two portions of the antenna are connected. The single-wire line is connected at a point 0.18-wave length from one end of the antenna, giving it a proper impedance match.

(4) Another common high-frequency, single-wire antenna is illustrated in figure 100. This delta-matched military antenna often is used with transmitters having output powers up to several kilowatts over distances of 500 miles or less for point-to-point, fixed-station communication. For transmission up to about 200 miles, the antenna height should be less than a quarter-wavelength in order to produce the required high angle of radiation. For longer distances, the antenna height may be as great as a half-wavelength to produce lower radiation angles.

(5) The antenna consists of a single, horizontal wire of about one half-wavelength. The power from the station transmitter is transferred from a balanced 600-ohm transmission line to the antenna by means of a delta-matching section. The ends of the wires of the transmission line are fanned out and attached to the antenna at equal distances from the center. The dimensions must be such as to match the line to the antenna so that the standing waves on the line are minimized. The exact dimensions depend on the antenna height, ground conditions, frequency, and the effect of structures near the antenna.

(6) A delta-matched, half-wave antenna used at a frequency of 5 mc would have the following dimensions (fig. 100): height, *H*, 70 feet, antenna length, *A*, 94 feet, maximum spread of matching section, *B*, 23.6 feet, and length of matching section, *C*, 29.5 feet.

65. Folded Dipole

a. Operation.

(1) The folded-dipole antenna consists of an ordinary half-wave antenna (dipole) which has one or more additional conductors connected across the ends of the antenna. The additional conductors are mounted parallel to the dipole elements at a distance that is a very small fraction of a wavelength in which spacings of several inches are common (fig. 101). In *A*, the two-wire folded dipole is constructed of metal tubing. In *B*, the three-wire folded dipole is made of wire. The electrical length of both antennas is a half-wave, which is about 95 percent of the free-space half-wavelength.

(2) Consider first the simple, two-wire folded dipole. Assume that the additional conductor is removed at points 1 and 2. Assume further that the charge remaining on the simple half-wave antenna is such that the end of the antenna at point 1 is maximum positive and the end of the antenna at point 2 is maximum negative. Ordinarily, current then would start to flow from point 2 toward point 1. Now, if the additional conductor is connected

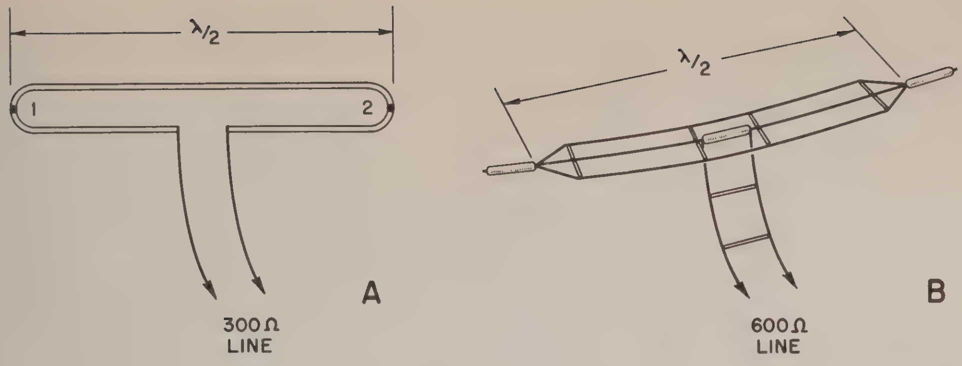

Figure 101. Folded-dipole antennas.

as shown in the figure, this current finds two paths available. Consequently, the current divides so that about half flows from right to left in the additional conductor, and the remaining half flows in the same direction in the lower conductor making up the simple half-wave antenna. This occurs with no change in input power.

(3) Since impedance varies inversely as the square of the current ($Z=P/I^2$), a reduction in the current flowing in that branch of the folded dipole to which the transmission line is connected results in an increase in the input impedance of the antenna. As the current is reduced to one-half its original value, the impedance of the antenna increases to four times 73 ohms, or close to 300 ohms. Therefore, a 300-ohm transmission line can be connected to the folded dipole, and a correct impedance match occurs.

(4) If three conductors are used instead of two, a given input power will produce only one-third the original current in each conductor. As a result, the input impedance of the antenna rises to nine times 73 ohms, or about 600 ohms. This provides the proper impedance match for an ordinary 600-ohm transmission line, and the folded dipole antenna provides an impedance step-up that can be used to affect an impedance match to common transmission lines.

b. Effect of Different Conductor Sizes.

(1) The folded dipoles discussed previously were constructed of conductors of equal diameter. If the added conductor has a larger diameter than the conductor to which the transmission line is connected, the impedance step-up produced by the folded dipole is increased. Under these conditions, the spacing between the two conductors has considerable effect on the impedance step-up.

(2) Assume that a folded dipole (fig. 102) is constructed so that the diameter of conductor No. 1 is *twice* the diameter of conductor No. 2. The effect of various spacings (S) is shown in the following chart, which gives the input impedance of this particular folded dipole arrangement:

Ratio of spacing (S) to diameter of conductor No. 2	Input impedance (ohms)	Ratio of spacing (S) to diameter of conductor No. 2	Input impedance (ohms)
2:1	730	12:1	360
4:1	440	25:1	330
8:1	365		

c. Radiation Pattern and Frequency Response.

(1) The radiation pattern produced by the folded dipole is similar to that produced by the conventional half-wave antenna. Maximum radiation occurs at right angles to the antenna itself and minimum radiation occurs off the antenna ends.

(2) An advantage of the folded dipole is that its characteristics do not change with frequency as much as do those of an ordinary dipole. Therefore, the folded dipole has a broader frequency response. This increased bandwidth is the result

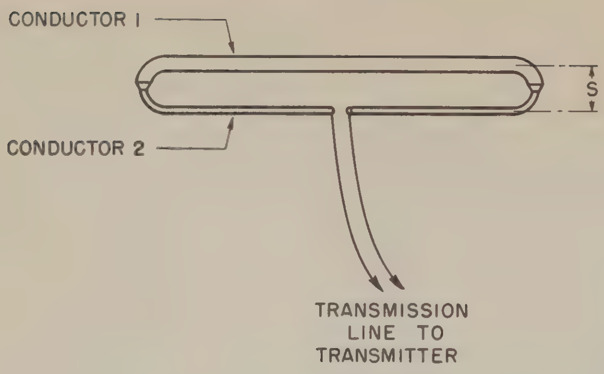

Figure 102. Folded dipole constructed of different conductor sizes.

of the greater cross-sectional area of the antenna which results from the folding. As a result, the folded dipole has greater capacitance and a smaller inductance per unit of length than does the ordinary dipole. The reduction in the *L-C* (inductance-capacitance) ratio of the antenna results in a lowered *Q* and a reduced frequency selectivity.

(3) The greater bandwith of the folded dipole is explained by the fact that it acts not only as an antenna but as two short-circuited quarter-wave transmission lines connected end to end (at the antenna center). Since the reactance at the center of an antenna varies in the opposite direction to the reactance at the end of a quarter-wave section of transmission line, the result is a reduction in the rate of reactance change which decreases the *Q* of the antenna and increases the frequency range.

66. Coaxial Antenna

a. Description and Operation.

(1) The coaxial or sleeve antenna is a common vertical radiator that is used in the vhf and uhf bands. In figure 103, the typical military coaxial antenna consists of a vertical half-wave antenna so constructed as to provide a convenient, mechanical feed arrangement. The antenna is fed by means of flexible coaxial cable which runs up through the supporting staff.

(2) The inner conductor of the coaxial cable is connected to the upper portion of the antenna, designated as the *whip*. The outer conductor of the cable is connected through a shorting ring to the top of an outer skirt. This skirt or sleeve is a hollow metal cylinder that is mounted around the outside of the mounting staff which supports the antenna. A small air space exists between the skirt and the outer surface of the mounting staff except at the location of the shorting ring. The skirt then acts as the lower portion of the antenna.

(3) The skirt has an additional function. In conjunction with the outer surface of the metal mounting staff, it forms a quarter-wave section of transmission line which is short-circuited at one end by the shorting ring. The impedance at the bottom end of the line so formed is very high. As a result, current flow is minimized on the mounting staff and on the outer conductor of the coaxial cable. Such current, if allowed to flow, would produce radiation at a high vertical angle. By reducing this current to a minimum value, the radiation is reduced. In this way, the low-angle, line-of-sight transmission required in the vhf and uhf bands is produced.

b. Dimensions.

(1) The dimensions of the whip and especially of the skirt are highly critical. The upper radiating portion (whip) (*A*, fig. 103) is made 95 percent of a free-space quarter-wavelength. The length of the lower radiating portion (skirt) (*B*) is made equal to a free-space quarter-wavelength. Actually, the skirt should be somewhat shorter than this value to produce maximum efficiency as a radiator. Its length, however, is chosen for best operation as a quarter-wave line, which produces slightly higher radiation efficiency. Adjusting clamps are provided both for the skirt and for the whip so that the antenna may be adjusted for any frequency in a given bank.

(2) One particular military coaxial antenna has a frequency range of from 30 to 40 mc. Another military coaxial antenna has a frequency range of 70 to 100 mc. Markings sometimes are provided on the elements themselves to show the correct

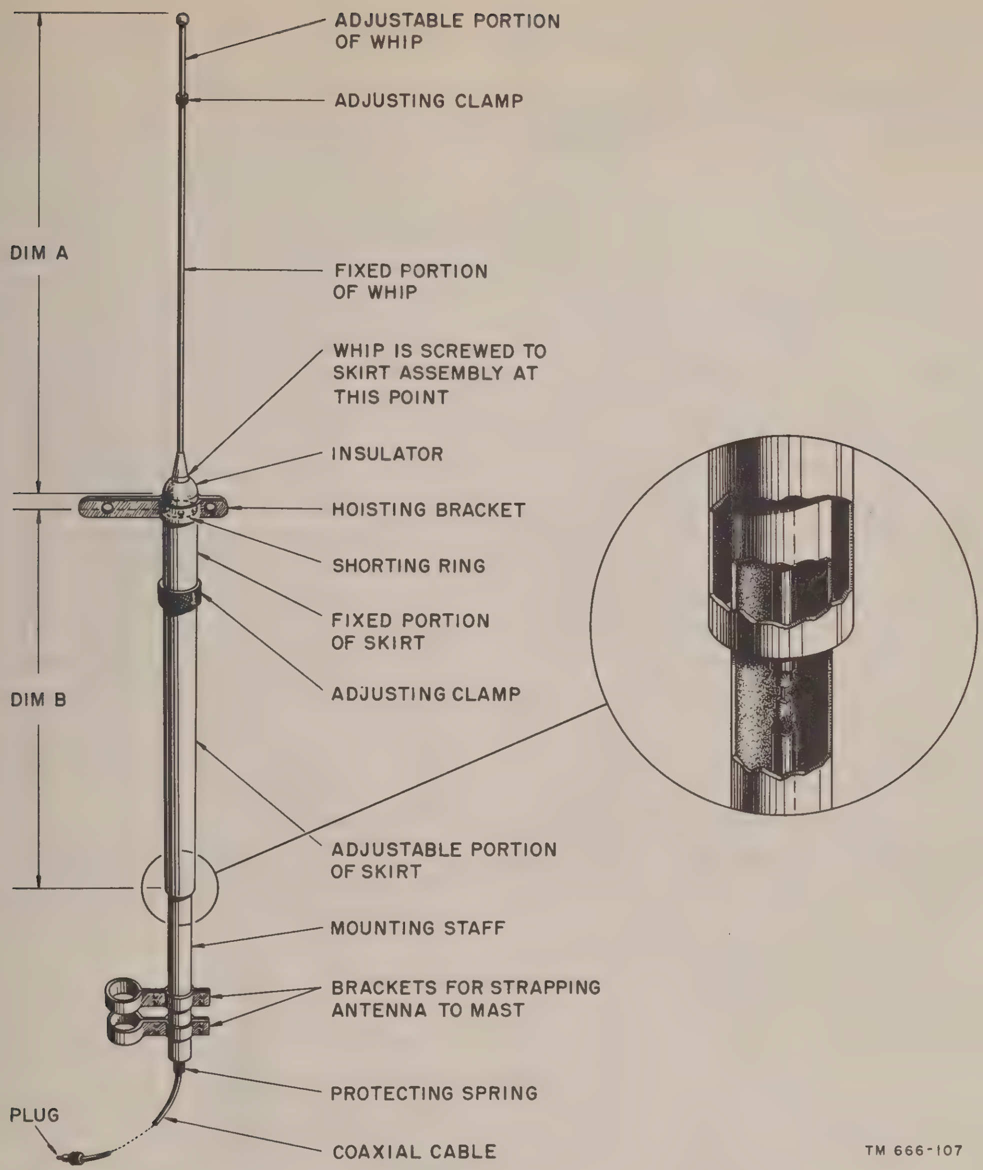

Figure 103. Military coaxial antenna.

whip and sleeve lengths for various resonant frequencies. For example, a coaxial antenna suitable for 35 mc would have a whip length of 80 inches and a skirt length of 84 inches.

c. Characteristics. The horizontal radiation pattern produced by the coaxial antenna is circular and, therefore, provides omnidirectional radiation or reception. Maximum radiation occurs at right angles to the antenna itself. The input impedance of a coaxial antenna is about 50 ohms, and a proper impedance match is produced when 50-ohm coaxial line is used.

67. Conical Antenna

a. Description and Characteristics.

(1) The conical antenna is one of a large number of special antennas that have been developed to operate satisfactorily over a wide frequency band. One type of conical antenna, constructed of two solid metal cones, is shown in figure 104. Frequently the conical antenna is constructed of metal mesh or is simply a framework of metal rods that forms the required shape. The cones are arranged

Figure 104. Simple conical antenna.

on a common horizontal or vertical axis, depending on whether horizontal or vertical polarization is required.

(2) If the conical antenna is to operate as a half-wave antenna, its over-all length must be considerably shorter than a free-space half-wavelength. This is the result of the large end effect produced by the bases of the cones forming the antenna. As the apex angle, A, is increased, the length of antenna required is reduced. For example, if angle A is 10°, the over-all length required is about 75 percent of a free-space half-wavelength. With angle A at 20°, the length is only about 70 percent of a free-space half-wavelength. When such short lengths are used, the input impedance is approximately 40 ohms. When the conical antenna is operated as a full-wave antenna, the over-all length commonly is made 73 percent of a free-space wavelength and the input impedance is several hundred ohms. When such an antenna has an apex angle of 10°, the input impedance is 950 ohms; with an apex angle of 20°, the input impedance is 600 ohms; with an apex angle of 30°, the input impedance is 300 ohms. The value may be reduced by using large apex angles, in excess of 30°.

(3) The large, cross-sectional area of the conical antenna accounts for its wide frequency response. Like the folded dipole, the conical antenna has a large capacitance but a small inductance per unit length. This reduces the effective Q of the antenna and causes its characteristics to change more slowly as the frequency is varied away from resonance. As the apex angle, A, increases, the bandwidth of the conical antenna increases. The radiation pattern of the conical antenna is similar to that produced by an

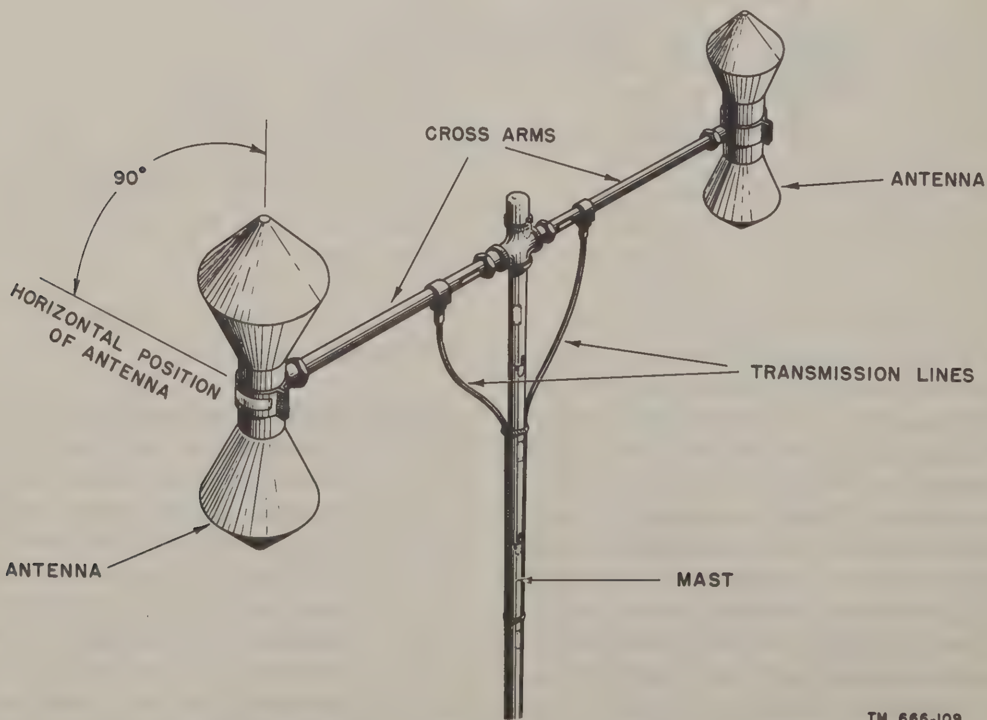

Figure 105. Typical military conical antenna assembly.

ordinary half-wave antenna which is similarly oriented.

b. Typical Military Antenna.

(1) The typical military conical antenna assembly shown in figure 105 consists of two modified conical antennas mounted at opposite ends of a cross arm atop a mast. The antennas can be mounted either as shown for the reception of vertically polarized signals, or they can be rotated through 90° for the reception of horizontally polarized signals. Each of these antennas has its own transmission line. These lines lead to separate input circuits of a vhf, uhf receiver.

(2) One antenna has an over-all length of slightly more than 23 inches, with a maximum cone diameter of 8½ inches. The other antenna has a length of about 16½ inches with a cone diameter of 6¼ inches. The larger antenna operates over a frequency range from 145 to 300 mc, the smaller antenna over a frequency range from 300 to 600 mc. Because of the large apex angle (about 60°), the variation in the input impedance of the antenna is very small over an extremely wide frequency range, and the antenna length is not particularly critical.

(3) The dimensions of the conical antenna were computed to maintain an impedance centered at about 95 ohms over the frequency range for which they were designed. Two shielded, two-wire lines having a characteristic impedance of 95 ohms are used to connect the antennas to the two input circuits of the receiver.

68. Microwave Antenna

a. The half-wave antenna can be used at any operating frequency. When microwave frequencies (at the upper part of the uhf band and higher) are used, the antenna length required is extremely small. For example, the microwave frequency of 5,000 mc has a free-space, half-wavelength of only a little more than 1 inch. The length of the half-wave antenna at this frequency would have a value somewhat less than this small distance.

b. The small size of a microwave, half-wave antenna is both a disadvantage and an advantage. The electrical characteristics of the microwave antenna are exactly like those of its larger, lower-frequency counterpart. It has about the same radiation pattern, the same distribution of standing waves along its length, and the same radiation resistance for similar conditions. However, the amount of signal pick-up when such a small antenna is used for receiving is reduced greatly. Any receiving antenna is able to pick up energy from a section of an incoming wave front that extends less than a quarter-wavelength away from the antenna. Therefore, a receiving antenna that is, say, 50 to 100 feet long is able to pick up a far greater amount of energy than can a microwave antenna only about an inch in length. So poor is the signal pick-up that a simple, half-wave antenna rarely is able to pick up enough microwave energy to overcome the noises generated within the receiver itself. As a result, a simple, half-wave antenna seldom is used alone in the microwave range.

c. The great advantage of the small size of microwave, half-wave antennas is that it becomes convenient to use a large number of these together to form an array of antennas. All antenna arrays have two things in common: First, an array produces a concentration of radiated energy in certain directions; that is, the array is highly directional—it has gain. Second, an array occupies a greater space than does the single, half-wave antenna, since it is made up of a number of half-wave antennas, and the greater the number of individual antennas that make up the array, the greater are the directivity and gain. In the microwave range, the construction of very elaborate arrays of half-wave antennas can be accomplished in a reasonably small space. Some microwave arrays are made up of as many as 32, 64, 100, or even 250 individual half-wave dipoles.

d. Other microwave antennas are composed of a single half-wave dipole or an array that is used in conjunction with specially shaped reflectors. These operate in much the same way as the parasitic reflectors (pars. 94 through 109) except that these reflectors are much larger than the dipole and they are specially shaped.

e. One commonly used reflector, shown in *A* of figure 106, is the corner-reflector type. The reflector is composed of two flat, metal sheets which meet at an angle to form a corner. Wire mesh or metal tubing sometimes is used instead of the solid metal. The half-wave, microwave antenna is located so that it bisects the corner angle because maximum radiation occurs out of

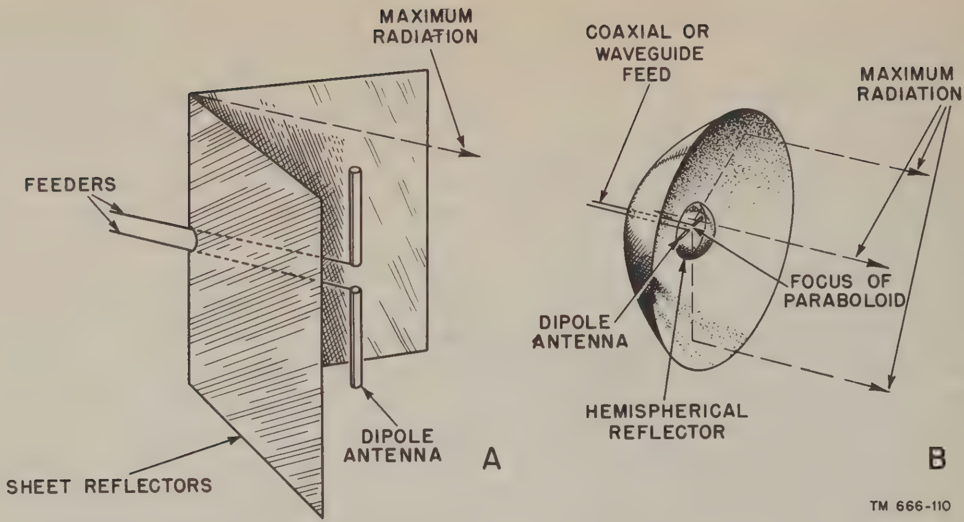

Figure 106. Half-wave antennas used with special reflectors.

the corner. The field strength produced by such an arrangement is considerably more than would be produced by the antenna alone.

f. Another commonly used reflector, shown in *B*, is the paraboloidal type. The shape is similar to that of reflectors used in searchlights that concentrate energy from a light bulb into a narrow, well defined beam. The reflector is constructed of solid metal or metal mesh. A half-wave, microwave antenna is located at the focal point of the paraboloid. Energy arriving at any angle from the antenna is reflected by the paraboloid in parallel rays. This results in a very narrow beam of radio energy in the direction shown. A small, metal, hemispherical reflector prevents direct radiation from the half-wave antenna from interfering with the beam produced by the paraboloidal reflector. The small reflector causes all of the energy from the antenna to be directed back into the paraboloid.

Section VI. GROUNDED ANTENNAS

69. Quarter-wave Antenna

a. The ground is a fairly good conductor for medium and low frequencies and acts as a large mirror for the radiated energy. This results in the ground reflecting a large amount of energy that is radiated downward from an antenna mounted over it. It is just as though a mirror image of the antenna is produced, the image being located the same distance below the surface of the ground as the actual antenna is located above it. Even in the high-frequency range and higher, many ground reflections occur, especially if the antenna is erected over highly conducting earth, salt water, or a ground screen.

b. Utilizing this characteristic of the ground, an antenna only a quarter-wavelength long can be made into the equivalent of a half-wave antenna. If such an antenna is erected vertically and its lower end is connected electrically to the ground (fig. 107), the quarter-wave antenna behaves like a half-wave antenna. Here, the ground takes the place of the missing quarter-wavelength, and the reflections supply that part of the radiated energy that normally would be supplied by the lower half of an ungrounded half-wave antenna.

c. When the charge on the quarter-wave grounded antenna is maximum positive at its upper end, the charge at the lower end of the image antenna is maximum negative. Current begins to flow toward the positive end of the quarter-wave antenna, as illustrated by the arrow in the figure. Current in the image antenna begins to flow away from the negative end of the image. Note that the current flow is up in both cases. This is similar to conditions in a vertical half-wave antenna that has negative polarity at the bottom and positive polarity at the top. It is just as though the half-wave antenna were driven halfway into the earth.

d. From figure 107, it must not be assumed that if a hole were dug into the earth under the antenna to a depth of a quarter-wave, conditions of voltage

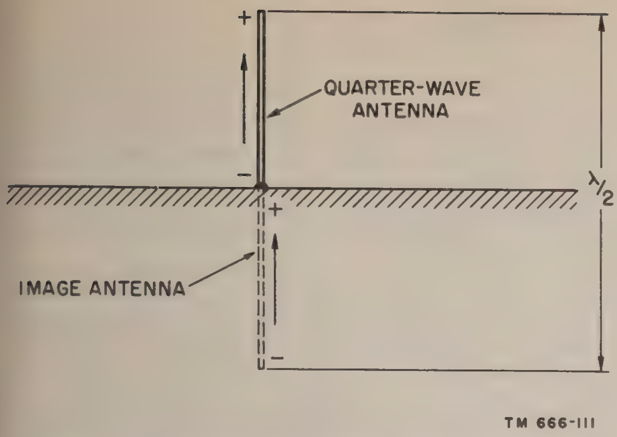

Figure 107. Quarter-wave antenna connected to ground.

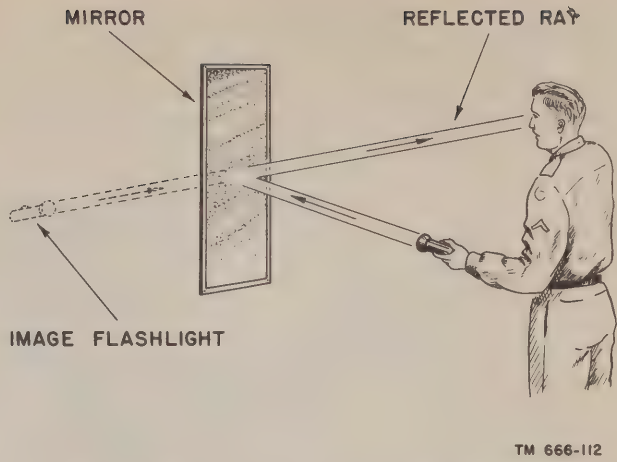

Figure 108. Formation of image flashlight.

and current such as described above would be found. Actually, this is not true, since the fields produced by the grounded quarter-wave antenna terminate only a short distance below the ground surface. None of the radiated field from the antenna penetrates the earth to any great extent. The following assumption with reference to a lighted flashlight will help to clarify the concept.

e. Assume that a soldier is standing before a mirror with a lighted flashlight in his hand (fig. 108). He holds the flashlight in such a way that its light is reflected by the mirror into his eyes; that is, the head of the actual flashlight is pointed away from him, whereas the head of the image flashlight is pointed toward him. This is a 180° shift in position. The effect is the same as if a flashlight were located behind the mirror the same distance as the actual flashlight is located before the mirror, without the mirror in the way. The image flashlight in the mirror is shining directly into the eyes of the soldier, although it is not a physical object as drawn in the figure, and if he looked behind the mirror he would find no flashlight. If the mirror were removed, there would be no reflected ray and the effect would be as though the image flashlight had disappeared.

f. The idea of an image flashlight can be applied to an image antenna formed by the ground. No antenna actually is located deep in the ground, but, because of the reflection of energy, conditions are similar to those that would occur without the reflecting surface and with a source of energy located as shown by the dashed lines in figures 107 and 108. Just as the position of the image flashlight is reversed, the polarity of charge on the image antenna is opposite to that of the actual antenna.

g. At medium and low frequencies, ground-wave transmission is used, which requires vertical polarization, and vertical antennas are necessary. If the half-wave antenna were used, an extremely tall structure would be required. At 1,000 kc, for example, the length of a vertical half-wave antenna would be almost 500 feet. When operated as a grounded type, the antenna need be only half that length, and loading devices make possible the use of even shorter lengths. These will be described below. Even in the high-frequency or very-high-frequency range, where the length of a half-wave antenna is much shorter, the use of the grounded quarter-wave antenna is common for portable and mobile installations. Here, resonant antennas of minimum length are required so that they can be carried easily by vehicles or by hand.

h. The term *Marconi antenna* sometimes is used to designate the grounded quarter-wave antenna, but this term is being replaced gradually by more descriptive terms which relate to specific types of grounded quarter-wave antennas. The term *Hertz antenna*, occasionally used to designate the ungrounded half-wave antenna, also is being replaced by more descriptive terms to designate specific antenna types.

70. Current and Voltage Distribution

a. The distribution of the standing waves of voltage and current on a grounded quarter-wave antenna is the same as the distribution on one-half of a half-wave antenna. The voltage is maximum and the current is zero at the end of the antenna farther from ground. As a result, the impedance which is the ratio of voltage to current, is highest at this point. The voltage and current vary in amplitude sinusoidally along the antenna; at the

grounded end of the antenna, the voltage is zero and the current is at its maximum value. As a result, the impedance is lowest at this point. The distribution of the standing waves of voltage and current is shown in *A* of figure 109.

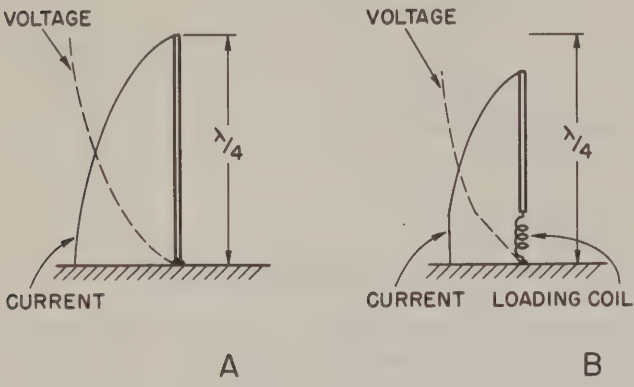

Figure 109. Distribution of voltage and current on grounded quarter-wave antenna.

b. Frequently, loading coils are used at the base of the grounded quarter-wave antenna. The added inductance of the loading coil reduces the resonant frequency of the antenna. This causes the antenna to appear as though it were longer electrically than it is physically, and grounded antennas which are shorter than a quarter-wave-length may be made to operate as quarter-wave antennas. The distribution of voltage and current on such an antenna are as shown in *B*. The current is zero at the ungrounded end of the antenna and rises sinusoidally along the antenna until the position of the loading coil is reached. The current then remains relatively uniform throughout the length of the coil. The voltage is at its maximum value at the ungrounded end of the antenna, falls sinusoidally until the coil is reached, and then falls uniformly to zero at the ground connection.

c. If a loading coil having a higher value of inductance is used, the length of the antenna can be reduced further. However, even though an extremely short antenna can be brought to resonance by a sufficiently large loading coil, the effective radiation of such an antenna is lowered and the ratio between the amount of power radiated and the amount of power dissipated in the resistance and ground connection of the coil is reduced considerably.

71. Polarization

a. The polarization of the radiated field produced by the grounded quarter-wave antenna is always vertical. Figure 110 shows the electric lines of force existing around the antenna at a particular instant of time.

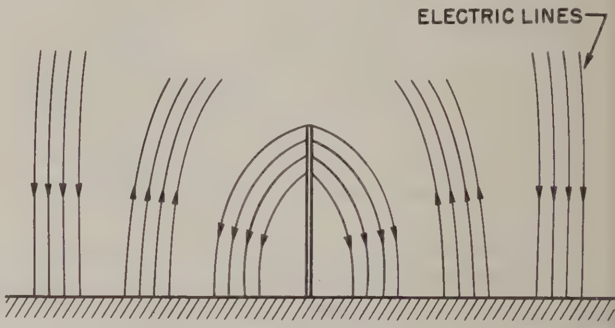

Figure 110. Electric field around a grounded quarter-wave antenna.

b. In some grounded antennas, a portion of the antenna is mounted horizontally. Even here, when short antenna lengths are used, a vertically polarized radio wave is produced, since the electric field is built up between the antenna and the ground rather than between one horizontal portion of the antenna and another horizontal portion.

72. Radiation Characteristics

a. *General*.

(1) The radiation pattern produced by a grounded quarter-wave antenna is shown in figure 111. It resembles the pattern of a vertical half-wave antenna in free space except that the latter pattern is cut in two horizontally. Maximum radiation (or reception) of energy occurs at right angles to the antenna and along the surface of the ground. The radiation falls off as the vertical angle is increased, until directly over the antenna (at a vertical angle of 90°), no radiation of energy occurs. A true semicircle is shown so that a comparison can be made with the radiation pattern.

(2) A top view of the radiation pattern shows that this pattern is circular. The antenna, therefore, is omnidirectional in the

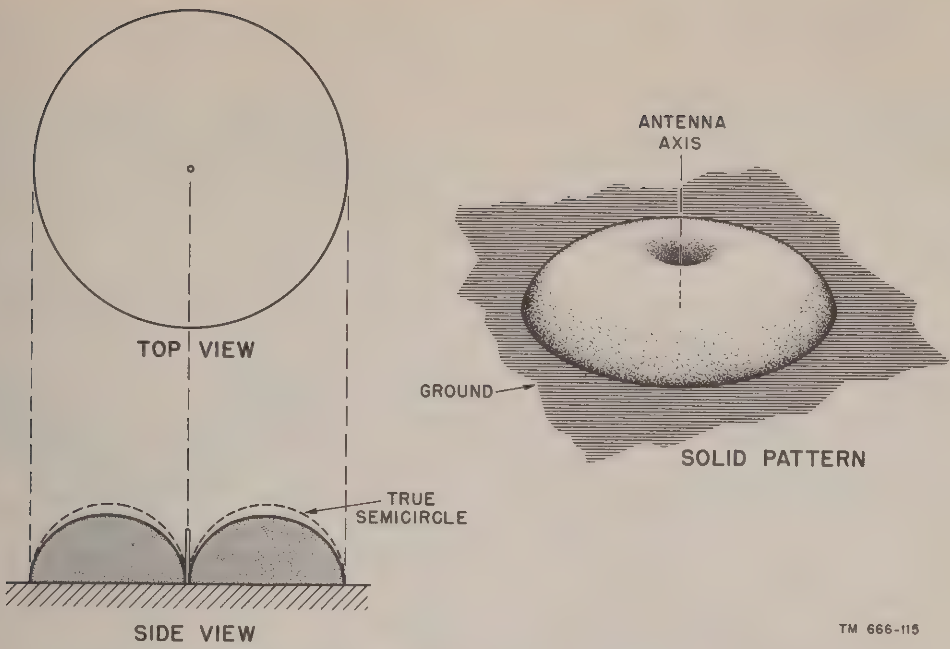

Figure 111. Radiation pattern produced by a grounded quarter-wave antenna.

horizontal plane, and radiates equally in all horizontal directions. The solid radiation pattern of the grounded quarter-wave antenna also is shown.

b. Other Radiation Patterns.

(1) Although most grounded vertical antennas are a quarter-wave length, it is common to find grounded antennas used with loading coils so that their length can be made shorter than a quarter-wave. The radiation patterns produced by such antennas are similar to the pattern shown in the previous illustration except that the amount of radiation is reduced and the side view of the pattern is practically a true semicircle.

(2) Consider next the vertical-plane radiation patterns of vertical antennas which are longer than a quarter-wave length. As the antenna length is increased to a half-wavelength, the amount of radiation is increased at very low vertical angles and the pattern becomes flatter (*A* of fig. 112). As the antenna length is increased still more toward 5 eighth-wavelengths, even greater radiation occurs at very low vertical angles. However, small minor lobes begin to appear at vertical angles of about 60°, as shown in *B*.

(3) If the antenna length is increased still more, the intensity of radiation at higher vertical angles is increased, as shown in *C* and *D*. Such antennas are not suitable for ground-wave transmission or for transmission of large amounts of energy in the horizontal direction.

c. Radiation Resistance.

(1) The radiation resistance of a grounded quarter-wave antenna is just half that of the ungrounded half-wave antenna. For very thin antennas, the value of the radiation resistance is 36 ohms. If large-diameter tubing or wide towers are used, the value is reduced.

(2) When grounded vertical antennas are used that are shorter than a quarter-wavelength, the radiation resistance is reduced still more. This can be seen in the following chart, where the value of radiation resistance is shown for vertical grounded antennas of various lengths.

Antenna lengths (wavelengths)	Radiation resistance (ohms)	Antenna lengths (wavelengths)	Radiation resistance (ohms)
0.30	60	0.15	8
0.25	36	0.10	2
0.20	20	0.05	1

(3) When very short antennas are used, it is

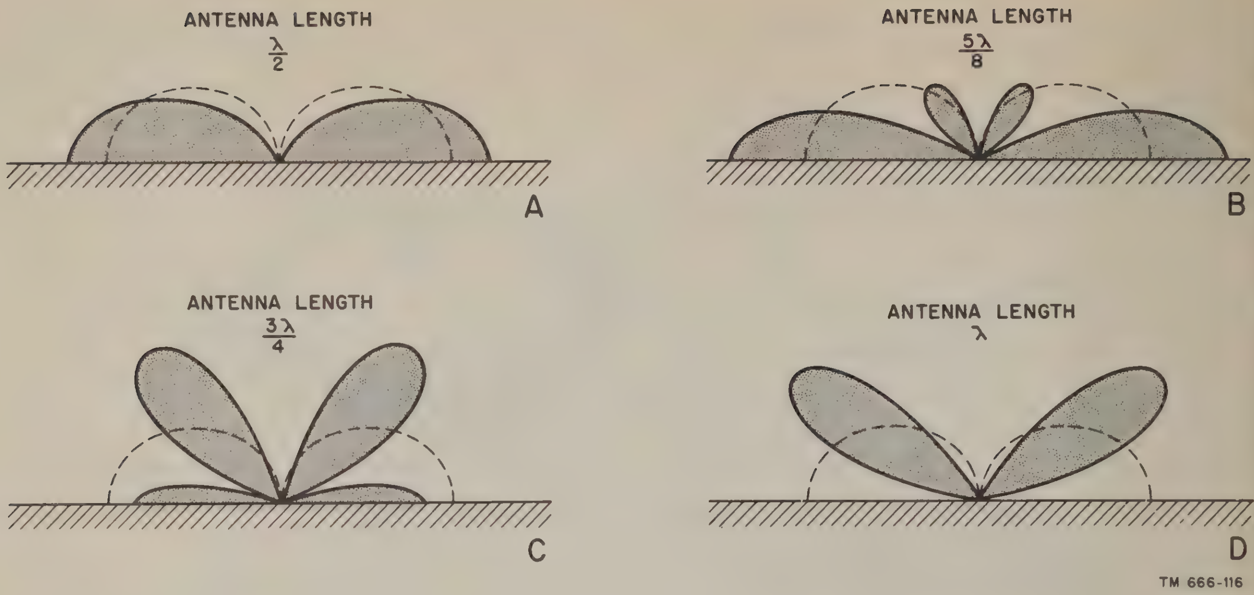

Figure 112. Vertical-plane radiation patterns produced by grounded vertical antennas of various lengths.

possible that the ohmic resistance of the antenna is considerably greater than the radiation resistance. For example, the ohmic resistance of the loading coil used might be several ohms, the resistance of the ground connection might be several ohms, and the resistance of the antenna itself might be 1 or 2 ohms, or more. The power that is dissipated in all these resistances may be considerably greater than the power that is radiated into space. If an antenna length used is .1 wavelength the radiation resistance is only 2 ohms, and the total ohmic resistance is 8 ohms.

(4) The power that is applied to this antenna is applied effectively to two resistances, one having a value of 2 ohms and the other having a value of 8 ohms. The input power is applied to a total resistance of 10 ohms. Since the power dissipated or radiated is directly proportional to the resistance, eight-tenths of the total power applied is used to overcome the antenna losses and only two-tenths of the total power applied produces useful radiation. Therefore, it can be seen how important it is to keep the ohmic resistance of the antenna as low as possible, to use a good ground connection, and to use a well designed loading coil.

(5) Once all the resistances that dissipate power uselessly have been reduced to an absolute minimum, the amount of energy radiated can be increased by increasing the radiation resistance of the antenna. One method of accomplishing this is to increase the length of the antenna toward a half-wavelength. At this length, the radiation resistance is about 100 ohms. The current maximum is no longer at the grounded end of the antenna but is instead halfway up the antenna. As a result, more energy is concentrated along the ground level and less energy is radiated at high vertical angles (*A* of fig. 106). In addition, since a greater portion of the antenna is carrying high current, a greater radiated field strength is produced.

73. Types of Grounds

a. General.

(1) When grounded antennas are used, it is especially important that the ground have as high a conductivity as possible. This is necessary to reduce ground losses and to provide the best possible reflecting surface for the down-going radiated energy from the antenna. Since at low and medium frequencies the ground acts as a sufficiently good conductor, the problem is how to make connection to the ground in such a way as to introduce the

least possible amount of resistance in the ground connection. At higher frequencies, artificial grounds constructed of large metal surfaces are common.

(2) The ground connection takes many forms, depending on the type of installation and the loss that can be tolerated. For fixed station installations, very elaborate ground systems are used. These frequently are arranged over very large areas so that they operate as part of the reflecting surface in addition to making the connection to ground itself. In many simple field installations, the ground connection is made by means of one or more metal rods driven into the earth. Where more satisfactory arrangements cannot be made, it may be possible to make ground connections to existing devices which are themselves grounded. Metal structures or underground pipe systems (such as water pipes) commonly are used as ground connections. In an emergency, a ground connection can be made by plunging one or more bayonets into the earth.

(3) Sometimes, when an antenna must be erected over soil having a very low conductivity, it is advisable to treat the soil directly to reduce its resistance. Occasionally, the soil is mixed with a quantity of coal dust for this purpose or it can be treated with substances which are highly conductive when in solution. Some of these substances, listed in order of preference, are sodium chloride (common salt), calcium chloride, copper sulphate (blue vitriol), magnesium sulphate (Epsom salt), and potassium nitrate (saltpeter). The amount required depends on the type of soil and its moisture content. When these substances are used, it is important that they do not get into nearby drinking water supplies.

b. Radial Grounds.

(1) The most common ground system used with vertical grounded antennas at fixed stations is the radial ground. This consists of a number of bare conductors arranged radially and connected. The conductors, which may be from a tenth- to a half-wavelength or more, are buried a short distance beneath the surface of the earth. Sometimes one radial ground system serves two vertical antennas which operate over different frequency ranges (fig. 113).

(2) Both antennas are constructed of several conductors connected to form a cage. Antenna A is used over a frequency range of 7 to 12 mc; antenna B is used over a frequency range of 2.5 to 7 mc. Each antenna is connected to the transmitter by means of a feed-through insulator (mounted on the wall of the transmitter house). Horn gaps, mounted on the insulators and connected to ground rods, provide lightning protection for the antennas and transmitter. The guys and horizontal supporting wire are broken up by insulators to prevent resonance effects which would cause absorption of power from the antennas. All of the radials forming the ground system are bonded together at the center and connected to the transmitter ground.

(3) A common military ground system kit which is supplied for use with grounded vertical radiators consists of 36 radials made of #12 Copperweld wire. These radials, spaced every 10°, extend outward for a distance of at least 350 feet from a common terminal near the lower end of the antenna. The conductors are buried in trenches, 6 to 8 inches deep. Soldered to the free end of each radial conductor a 6-foot ground rod is driven into the earth.

c. Ground Rods.

(1) With a less elaborate ground system, a number of ground rods can be used. These rods usually are made of galvanized iron, steel, or copperplated steel in lengths up to 8 feet. One end of the rod is pointed so that it can be driven easily into the earth. The other end frequently is fitted with some type of clamp so that the ground lead can be attached. Some ground rods are supplied with a length of ground lead already attached.

(2) A fairly good ground connection can be made by using several ground rods, 6 to 10 feet apart, connected in parallel. If possible, the rods should be located in a

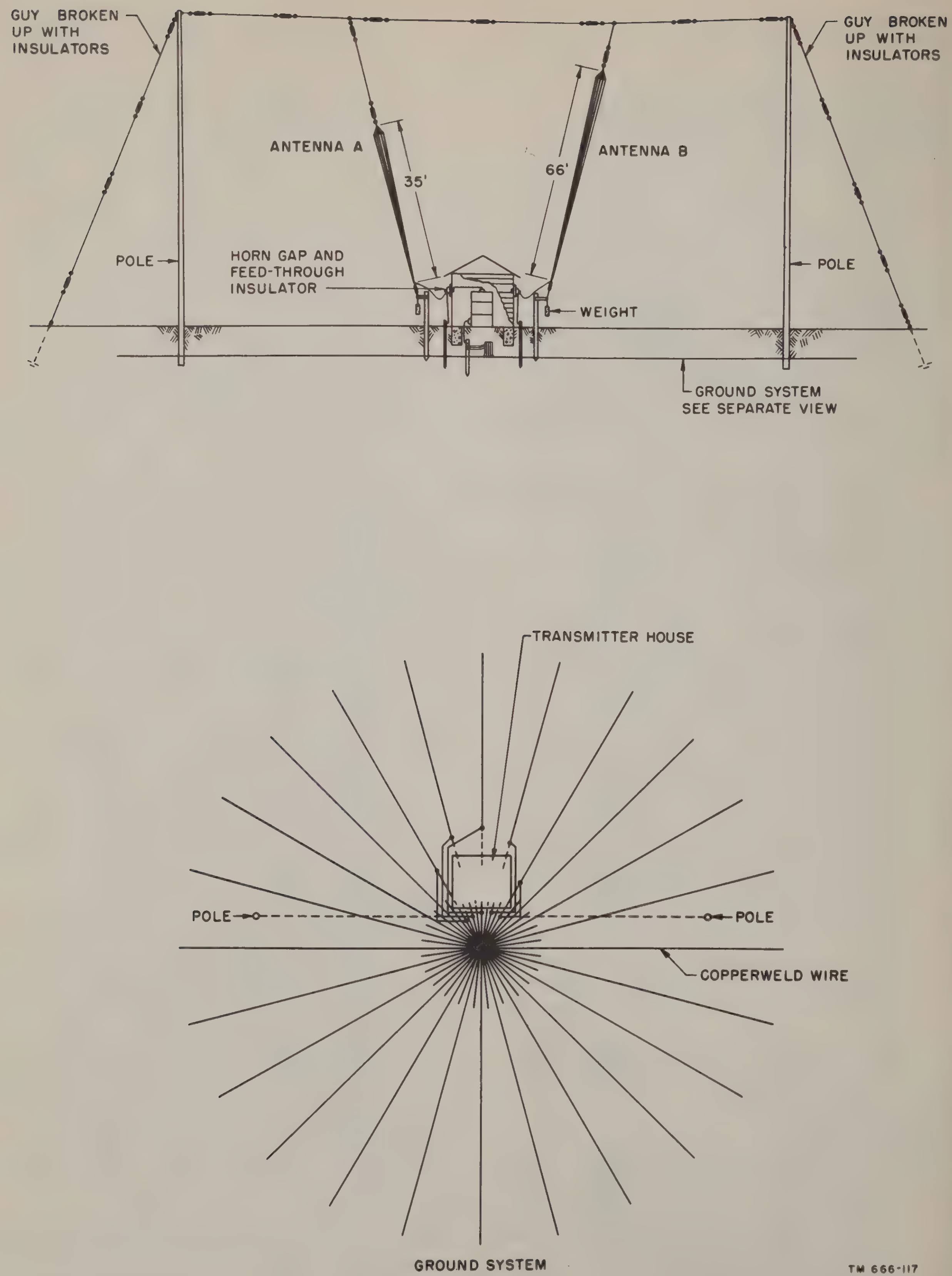

Figure 113. Ground system for two vertical antennas.

moist section of ground or in a depression which will collect moisture. Ground resistance can be reduced considerably by treating the soil with any of the substances previously mentioned. A trench about a foot deep is dug around each ground rod and filled with some common rock salt, Epsom salt, or any of the other materials mentioned. The trench then is flooded with water, after which it is covered with earth. To remain effective, this treatment should be renewed every few years.

(3) For simple installations, a single ground rod can be fabricated in the field from pipe or conduit. It is important that a low resistance connection be made between the ground wire and the ground rod. The rod should be cleaned thoroughly by scraping and sandpapering at the point where the connection is to be made, and a clean ground clamp installed. A ground wire then can be soldered or joined to the clamp. The joint should be covered with tape to prevent an increase in resistance caused by oxidation.

d. Counterpoise.

(1) When an actual ground connection cannot be used because of the high resistance of the soil or because a large buried ground system is not practicable, a counterpoise may replace the usual direct ground connection in which current actually flows to and from the antenna through the ground itself. The counterpoise consists of a structure made of wire erected a short distance off the ground and insulated from the ground. The size of the counterpoise should be at least equal to and preferably larger than the size of the antenna.

(2) The counterpoise operates by virtue of its capacitance to ground. Because of this capacitance, the ground currents which flow normally and usually are collected by conduction now are collected in the form of charge and discharge currents. The end of the antenna which normally is connected directly to ground now is connected to ground through the large capacitance formed by the counterpoise. If the counterpoise is not well insulated from ground, the effect is much the same as that of a leaky capacitor. Leakage currents flow between the counterpoise and ground so that a poorly insulated counterpoise introduces more losses than no counterpoise at all.

(3) The shape and size of the counterpoise are not particularly critical. In some field antenna installations, a type of grounded antenna is used in which a large portion of the antenna is folded into a horizontal position. The counterpoise used with such an antenna has the same shape and approximate dimensions as does the antenna itself. This counterpoise is mounted directly under the antenna at a height of about 8 to 12 feet off the ground.

(4) When the antenna is mounted vertically, the counterpoise is made to have any simple geometrical pattern such as those shown in figure 114. Although perfect symmetry is not necessary, the counterpoise should extend for equal distances at all angles from the antenna. The area covered by the counterpoise should be as great as possible, although very little is gained by extending the counterpoise more than a half-wavelength from the lower end of the antenna. The distance between parallel adjacent wires making up the counterpoise should be about equal to the height of the counterpoise above ground, because long conductors become resonant and absorb power from the antennas. To avoid this, the use of short jumpers between the conductors causes the counterpoise to behave only as a capacitance to ground. Smaller

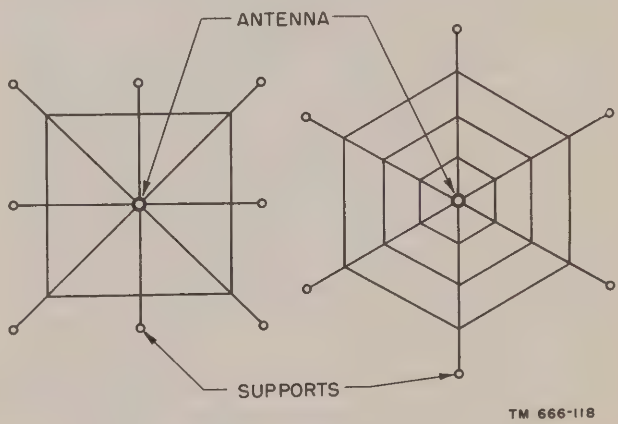

Figure 114. Wire counterpoises.

separations should be used with small counterpoises.

(5) In some vhf antenna installations on vehicles, the metal roof of the vehicle is used as a counterpoise for the antenna. Small counterpoises made of metal mesh sometimes are used with special vhf antennas that must be located a considerable distance off the ground. This counterpoise provides an artificial ground which helps to produce the required radiation pattern.

74. Bent Antenna

a. Description and Operation.

(1) A bent antenna is a grounded antenna so constructed that a portion of it is mounted horizontally. Such an antenna takes the form of an inverted L or T. In an inverted-L antenna, a fairly long horizontal portion, or flattop, is used, and the vertical downlead, which forms an important part of the radiating system, is connected to one end of the flattop. The length of the antenna is measured from the far end of the flattop to the point at which the downlead is connected to the transmitter. In the T antenna, a horizontal portion, or flattop, also is used. Here the downlead, which is a part of the radiating system, is connected to the center of the flattop. The over-all length of the T antenna is equal to the entire length of the downlead plus one-half the length of the flattop.

(2) The purpose of the bent antenna is to afford satisfactory operation when it is not convenient to erect tall vertical antennas. This is particularly necessary when operation at low frequencies is required.

(3) When the length of the flattop of a bent antenna (the entire length of the inverted L or one-half the entire length of the T) is 1 quarter-wavelength long, a full quarter-wave of current appears as a standing wave on the flattop. The current is minimum at the far end of the flattop and maximum at the point where the downlead is connected. Since the current maximum is no longer at the ground level (as it is in a grounded antenna of a quarter-wavelength or less), but is elevated above ground by the length of the vertical downlead, there are several advantages. First, the high-angle radiation is reduced and more energy is propagated along the surface of the earth. This is particularly important when ground-wave transmission is used. Second, because more of the antenna is carrying a high value of current, a greater amount of radiation occurs.

(4) When the vertical downlead of a bent antenna is approximately a quarter-wavelength, the current in the downlead falls to a minimum value at the end connected to the transmitter. Here the radiation resistance of the antenna has a high value because the ratio between the radiation resistance and the ohmic resistance of the antenna is a maximum, and a large proportion of the power applied to the antenna is radiated. When using a downlead of 1 quarter-wave, a parallel resonant circuit should be employed for antenna tuning which requires high impedance for proper impedance matching; but if the downlead is 1 eighth-wavelength or shorter, series tuning is used to provide the required low impedance.

(5) Even when very short vertical downleads are used, the addition of a horizontal flattop to form a bent antenna produces the advantages mentioned above. Bent antennas of only a quarter-wavelength (including downlead) frequently are used in the field. The radiation produced by such antennas is considerably greater than would be produced by a simple vertical antenna having the same length as the height of the bent antenna.

(6) When bent antennas are used at low frequencies, it is common to construct the flattop of several connected conductors. This increases considerably the capacitance between the flattop and the ground. As a result, the resonant frequency of the antenna is reduced, and the antenna operates as a simple vertical antenna of much greater height. The higher capacitance produced by this type

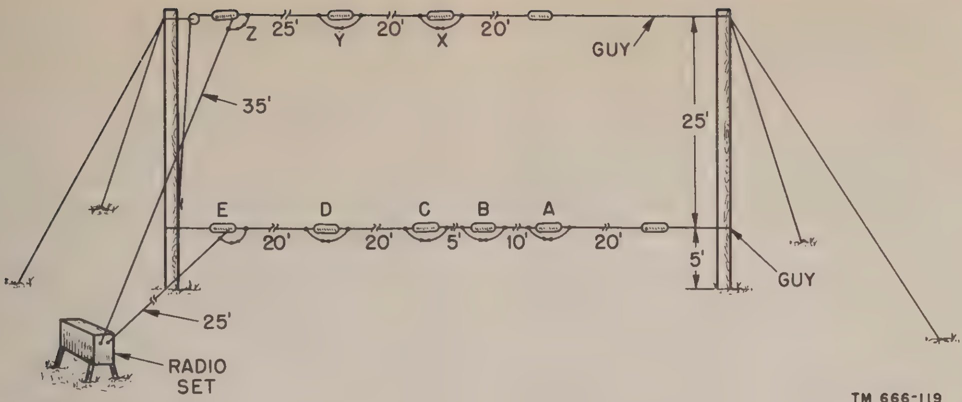

Figure 115. Inverted-L military antenna.

of flattop raises the position of the current maximum still higher above the ground, with the resultant advantages previously pointed out.

b. Military Types.

(1) One common military bent antenna used at frequencies from about 1.5 to 12.5 mc (fig. 115) is an inverted-L type with a single-wire counterpoise. This antenna is designed to operate with a total length of about 1 quarter-wavelength at a lower portion of its frequency range and 3 quarter-wavelengths at the upper portion. It affords a low-impedance load on the radio set with which it is used. This antenna is particularly suitable for ground-wave transmission, although it is very efficient for sky-wave use.

(2) Small jumpers are provided at the various insulators so that these may be shorted out if it is required to increase the length of the flattop and counterpoise. Clip leads at E and Z connect the counterpoise and the flattop to the leads which run to the radio set. When operation from 1.5 to 2 mc or from 4.5 to 6 mc is required, all jumpers are connected so that the lengths of the antenna and the counterpoise are each 100 feet. When operation from 2 to 3 mc or from 6 to 9 mc is required, the

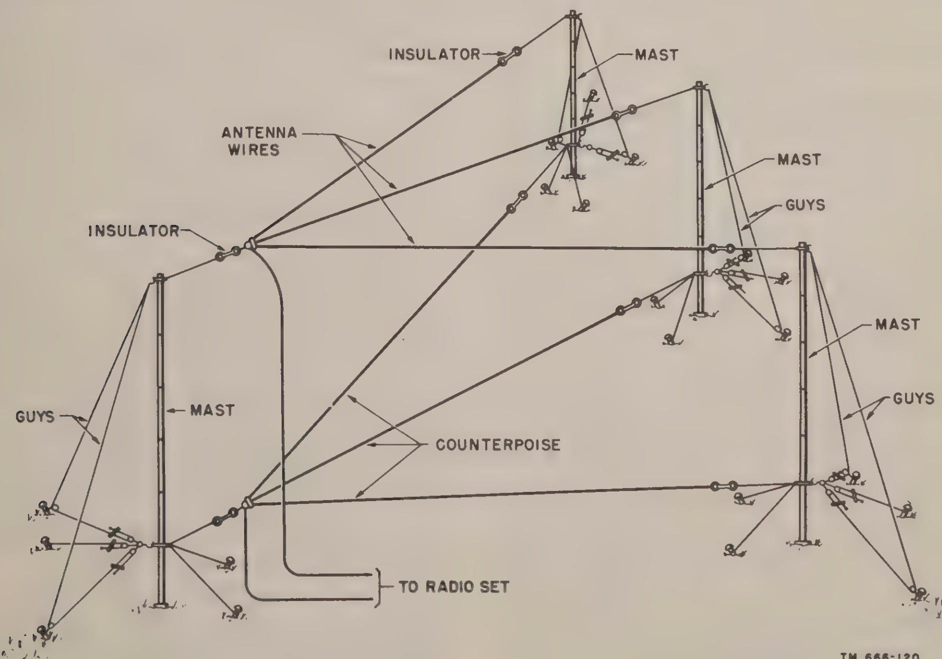

Figure 116. Crowfoot antenna.

connections at A and X are broken. The antenna and the counterpoise then are each 80 feet long. When operation from 3 to 4.5 mc or from 9 to 12.5 mc is required, the connections at A, B, C, D, X, and Y are broken, making the length of the antenna 60 feet and the length of the counterpoise 45 feet.

(3) Another inverted-L antenna used for military communication in the frequency range below 800 kc consists of a flattop constructed of five parallel conductors from 250 to 400 feet long and separated from each other by about 3 feet. The vertical downlead is connected to each of the flattop conductors at one end of the antenna. An extensive underground radial ground system is used with this antenna.

(4) Still another inverted-L antenna used for low-frequency military communication is shown in figure 116. The flattop is seen to consist of three conductors, each 100 feet long, which are joined at one end and fan out at the other end to a maximum separation of about 30 feet. A counterpoise is used with this antenna, which is shaped like the flattop. Because of the appearance of this antenna, it commonly is referred to as a *crowfoot antenna*.

75. Folded-top Antenna

a. A folded-top antenna is a modified bent antenna in which the flattop is folded in such a way that it prevents radiation. If radiation from the flattop is prevented, or at least reduced considerably, more energy can be radiated from the vertical downlead of the antenna. The main advantage of preventing radiation from the horizontal flattop is that this part of the antenna may produce considerable radiation that is horizontally polarized. In addition, this energy is radiated at high vertical angles. Since the radiation does not add to the vertically polarized ground wave required, its elimination will improve the operation of the antenna. Another advantage of the folded-top antenna is that less horizontal space is required for its erection.

b. The simplest method of preventing radiation of energy from the flattop portion of the antenna is to fold the flattop in such a way that adjacent sections carry current flowing in opposite directions. In this way, the field produced around one section is opposite in direction to that produced around the adjacent section. As a result, almost complete cancellation of fields occurs, and radiation is largely prevented. Unless an *even* number of sections is used, appreciable cancellation will not occur.

c. Two folded-top antennas are shown in figure 117. In both cases, the quarter-wave flattop which is required to bring the current maximum to the top of the vertical downlead is folded in such a way as to prevent radiation from the flattop. In A, the downlead to the transmitter is connected to one end of the folded section. This section consists of a quarter-wavelength of wire that is doubled back on itself so that the over-all length of the folded section is an eighth-wavelength. Note that the two wires forming the folded section are connected at the left and are not connected at the right. At any instant, the current in the two wires flows in opposite directions as shown by the arrows. Consequently, the field produced by one conductor is opposite in direction to that produced by the other conductor. Therefore, negligible radiation occurs from the folded section.

d. In B, the downlead is connected to the center of the folded flattop. Note that the downlead is connected to the left half of one of the two conductors forming the folded top, and the direction of current flow in the folded quarter-wave section is as indicated by the arrows. Other arrangements can be used in addition to those shown. For example, the top quarter-wave section can be folded into four lengths, each of which is a sixteenth-wavelength long.

76. Top-loaded Antenna

a. Both the bent and folded top antennas operate at frequencies that are much lower than the length of the vertical portion of the antenna would seem to indicate. The length not supplied by the vertical downlead is furnished by the bent or folded flattop. As a result, the standing wave of current appears higher on the vertical section of the antenna and its radiation resistance rises. Consequently, greater effective radiation occurs and at smaller vertical angles.

b. Another method of increasing the effective length of a vertical antenna to obtain these advantages is to use *top loading*. This usually is accomplished by adding a concentrated amount of

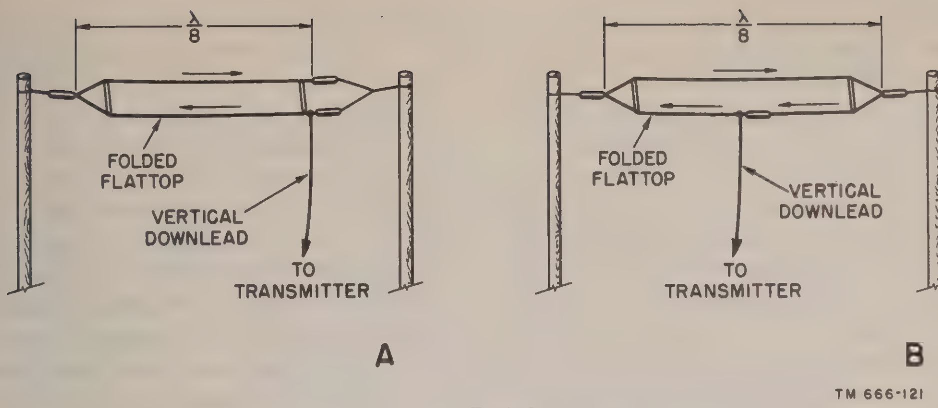

Figure 117. Folded-top antennas.

capacitance or inductance at or near the top of the vertical antenna. Such an antenna is a *top-loaded* antenna.

c. When inductance is used, the inductor simply is inserted in series with the antenna near the top. When capacitance is used, a capacitor *cannot* be inserted in series with the antenna, since this would reduce the total capacitance of the antenna, making it appear electrically *shorter* rather than longer as is desired. Shunt capacitance must be used instead so that the total capacitance between the antenna and ground is increased. The most common method of producing the required shunt capacitance is to use a disk or a *hat* made of sheet metal, mesh, or wire skeleton. The disk is centered on the top of the antenna and mounted at right angles to it. Such an arrangement provides an added capacitance of about 1 $\mu\mu$f (micromicrofarads) for each inch of disk diameter.

d. Sometimes both inductance and capacitance are used. The hat then must be insulated from the top of the vertical antenna and an inductor inserted between the hat and the antenna. The inductor frequently is made variable so that an adjustment of the amount of the top-loading is possible. This is more convenient than trying to make such an adjustment by varying the amount of shunt capacitance, since this would involve a change in the size of the top-loading disk.

e. In some portable or mobile installations where top loading is used, the top-loading coil is inserted near the top of the antenna and a large metal shield is installed around the coil. The shield not only affords protection for the coil but also provides some shunt capacitance for top-loading the antenna. Where the top-loading coil and its shield would cause the antenna to be unstable physically because of top-heaviness, the coil and shield are moved to the center of the antenna. Although this is not as effective as true top-loading, the radiation produced by such a center-loaded antenna is better than would be produced by a single loading coil at the base of the antenna or in the transmitter itself.

f. The low-frequency bent antennas already discussed actually use some top-loading to increase the electrical length of the antenna and to produce the advantages mentioned above. The antennas shown in figure 116 utilize two or more insulators as the flattop to provide an increase in shunt capacitance. The term *top-loaded antenna*, however, usually refers only to those vertical antennas in which the shunt capacitance is supplied by a structure (such as a disk) the size of which is small compared with the length of the antenna. Because of the small size of the top-loading disk, little radiation is produced.

g. Figure 118 shows the current distribution on top-loaded antennas which are somewhat shorter than a quarter-wavelength. The current is the same as would be produced if the top-loading disk or coil were removed and the actual height of the antenna extended as shown.

h. In general, as the ground resistance is

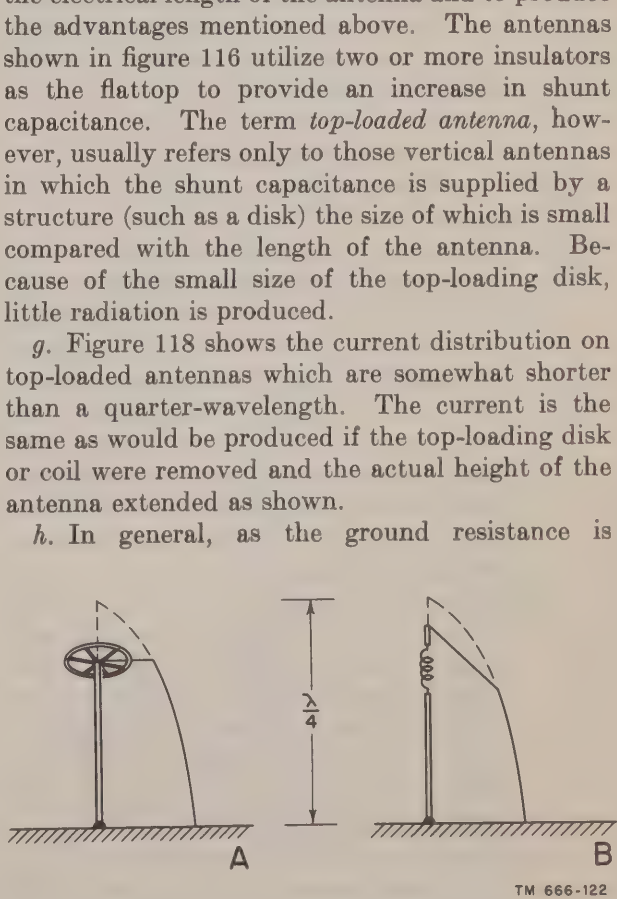

Figure 118. Top-loaded antennas.

increased, the size of the top-loading disk can be reduced. However, large ground resistances require top-loading coils with higher inductance values. As the size of the top-loading disk is increased, the effective length of the antenna is increased. For example, the length of the antenna shown in *A* can be reduced further physically if the top-loading disk is increased in size. The actual size of the top-loading disk or coil required has been determined experimentally for a large number of special cases.

i. It is desirable to increase the radiation resistance of an antenna so that a greater proportion of the input power can be radiated. Assume that a vertical antenna having a length of 0.2 wavelength, used without a top-loading disk, has a radiation resistance of 20 ohms. If a small top-loading disk is installed which has such a size as to increase the effective length of the antennas by about 0.05 wavelength, the radiation resistance is increased to 34 ohms. If the size of the disk is increased so that the effective length of the antenna is increased by about 0.1 wavelength, the radiation resistance rises to 45 ohms. A further increase in disk size, so that the effective antenna length is increased by about 0.15 wavelength, causes the radiation resistance to rise to 50 ohms.

77. Mast and Tower Radiators

a. Description.

(1) Most of the antennas discussed so far have been constructed of suitably supported wire. Since vertical supports are required for such antennas, it seems reasonable to consider use of the support itself as the antenna. This support must be constructed of metal so that it can be used as the antenna. Metal masts are used in the field and large metal towers are used for fixed-station installation as vertical radiators.

(2) Metal masts usually are made of aluminum alloy or steel tubing, sectionalized with metal coupling so that they can be taken apart for easy portability. Some short antenna masts, approximately 25 feet high, use a telescoping section construction. Masts usually are supported by means of guys.

(3) Metal antenna towers are designed to be either self-supporting or guyed. Both three-sided (triangular) and four-sided (square) construction is common. The self-supporting tower has a wide base so that no guying is needed. The guyed tower, on the other hand, usually has a fairly uniform cross section.

(4) Mast and tower radiators can be subdivided into insulated and noninsulated types. An insulated mast or tower uses special compression-type base insulators that carry the weight of the structure and handle the r-f voltage that exists. A spark gap is used across the base insulator for lightning protection (fig. 119). In noninsulated towers and masts, the base of the structure is in direct contact with the base support which is in the earth. When the insulated tower is used, the energy applied to the tower must be series-fed. Shunt feeding is used with the noninsulated tower.

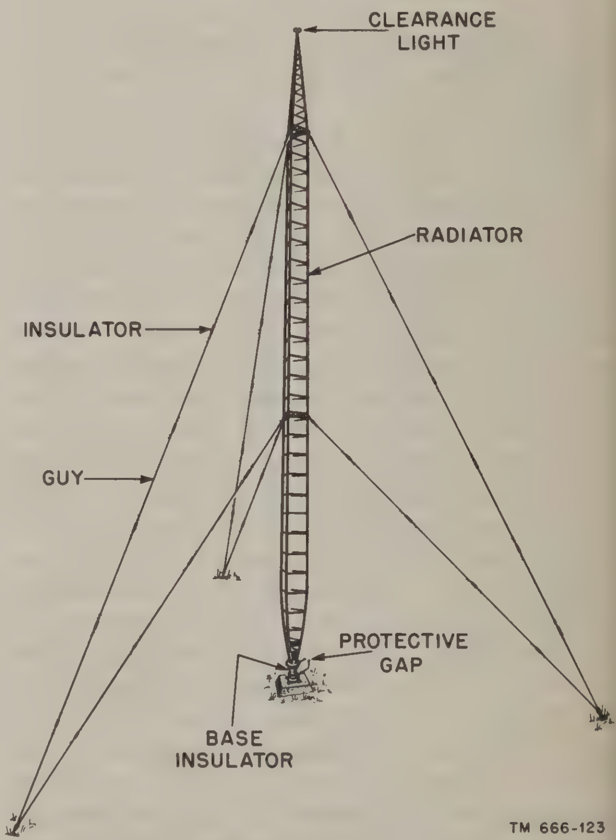

Figure 119. Typical insulated guyed-tower radiator.

b. Operation.

(1) The operation and radiation of a mast or tower radiator are similar to the operation and radiation of a grounded vertical

antenna constructed of wire. Because of the greater cross-sectional area of these radiators, reduction of ohmic resistance results in a slight increase in over-all efficiency and in electrical length.

(2) When a self-supporting tower is used, the tapering construction of the tower alters the current distribution so that it is no longer sinusoidal. Instead of the current rising sinusoidally at increasing distances from the tower top, the current increase is somewhat more gradual. Since the electrical length of the tower is *reduced*, the radiation resistance falls, and increased high-angle radiation occurs. This condition is reduced by adding a top-loading disk or hat on top of the tower.

(3) When insulated masts or towers are used, the output of the transmitter is applied between the lower end of the structure and ground. The transmitter output is, in effect, connected directly across the base insulator (S), as shown in *A* of figure 120, and is referred to as series feeding.

(4) The output of the transmitter is connected through a capacitor to point *X*, about one-fifth of the way up the tower. The inclined wire usually makes an angle of about 45° with respect to ground. The exciting voltage from the transmitter is developed between point *X* and ground, across the lower section of the tower. This section can be considered to be a portion of a one-turn loop made up of the inclined wire (with capacitor), the portion of the tower between point *X* and ground, and the ground return between the bottom of the tower and the transmission-line ground connection. Since the transmission line usually sees an inductive reactance in the direction of point *X*, a series capacitor is used to cancel out this reactance. Noninsulated masts or towers using this arrangement are shown in *B*.

c. Military Types.

(1) One type of tower radiator used for military communication involving transmitter powers of several kw (kilowatts) is 180 feet high and is guyed for support. The tower is an insulated type using a single compression insulator at its pointed base. The tower consists of nine 20-foot sections, triangular in shape and lattice braced, with guys at five different levels, three guys to each level.

(2) Another military tower radiator used for transmitter powers up to about 1 kw is 125 feet high and is self-supporting, a square construction with insulators being used at the tower base.

(3) Still another military tower radiator used for transmitter powers up to about 1 kw is 90 feet high and is guyed for support. This tower is an insulated type with

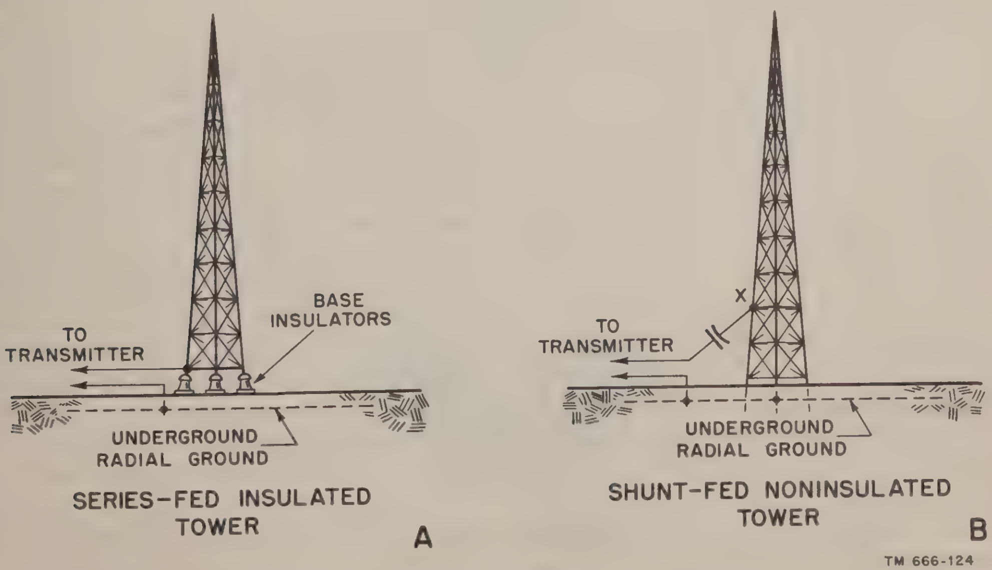

Figure 120. Series- and shunt-fed tower radiators.

triangular, lattice construction, equipped with one set of guys located 30 feet from the tower top.

78. Ground-plane Antenna

a. A ground-plane antenna consists of a quarter-wave vertical radiator which, in effect, carries its own artificial ground. The artificial ground or ground plane consists of a flat disk of metal or a number of metal rods or spokes located at the bottom of the radiator and usually at right angles to it (*A* of fig. 121). Since the metal disk or spokes are not connected directly to ground, they may be referred to as a counterpoise. This term is used rarely, however, this part of the antenna usually being called simply an *elevated ground plane*.

b. The ground-plane antenna is used when nondirectional horizontal radiation or reception is required. It is particularly useful in the very-high-frequency range and higher. At these frequencies, the length of a vertical quarter-wave antenna is not great. Any desire to operate such an antenna in conjunction with the actual ground would create high ground losses and would prevent

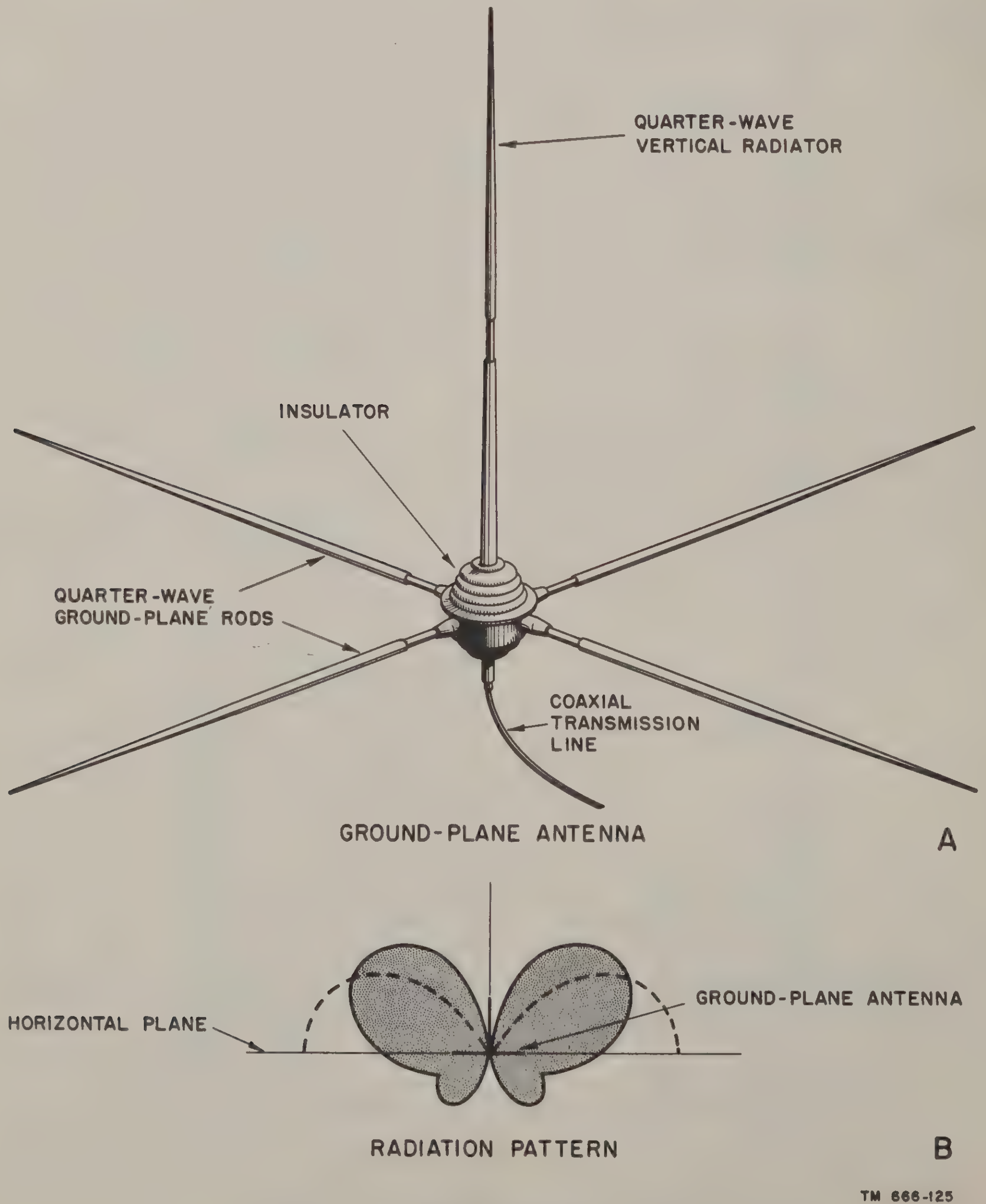

Figure 121. Typical ground-plane antenna.

efficient radiation or reception. The ground-plane antenna, on the other hand, is usually well elevated so that ground losses are minimized.

c. The elevated ground plane also prevents circulating currents from flowing in a vertical metal mast that might be used to support the antenna. These currents, if not prevented, would cause the vertical support itself to radiate in the same manner as a long-wire antenna. As a result, undesired high-angle radiation would be produced.

d. The radiation produced by a vertical quarter-wave grounded antenna erected adjacent to the earth itself is maximum along the surface of the earth (at a vertical angle of 0°). The intensity of the radiation falls off at higher vertical angles until, at a vertical angle of 90°, no radiation occurs. A side view of this radiation pattern is shown dashed in *B* of figure 121. Since this type of radiation occurs at all horizontal angles, a top view of the pattern would be circular. When a ground-plane antenna is used, the limited size of the elevated ground plane alters the radiation as shown, and maximum radiation is no longer along the horizontal plane but occurs at some angle above.

e. When maximum radiation is required in the horizontal direction, it is common practice to bend down the spokes forming the elevated ground plane to an angle of about 50° below the horizontal. When the solid metal construction is used, the elevated ground plane takes the form of a cone, and the lobes of maximum radiation, shown in *B*, are pulled downward to a much lower vertical angle.

f. In almost all cases, coaxial line is used to feed the ground-plane antenna. The inner conductor of the coaxial line is connected to the quarter-wave vertical radiator; the outer conductor is connected to the elevated ground plane.

g. The input impedance of a ground-plane antenna with elevated ground plane at right angles to the radiator is between 20 and 25 ohms. Since this is a lower value of impedance than is found in most coaxial lines, a quarter-wave matching section sometimes is inserted between the antenna and its transmission line. The matching section can be constructed of two quarter-wave sections of coaxial line connected in parallel to produce the required low impedance. In some ground-plane antennas, the radiator is folded back on itself so that it resembles one-half of a folded dipole. Under these conditions, the input impedance of the antenna is raised to about 80 ohms, so that a coaxial transmission line having a characteristic impedance near this value can be used. When the ground-plane rods are bent downward below the horizontal, the input impedance is raised to about 50 ohms.

79. Whip Antenna

a. The most common antenna used for tactical radio communication when relatively short distances are to be covered is the *whip antenna* (fig. 122). This term is applied to almost any type of flexible radiator used in conjunction with portable or mobile radio equipment. Whip antennas ranging in length up to 25 feet are mounted on vehicles. Shorter whip antennas are mounted on small hand-held radio sets or portable sets used in the field.

b. Most whip antennas are constructed of telescoping sections of metal tubing which can be collapsed when not in use simply by pushing one section into another. In this way, the antenna has a minimum length and portability is increased. In certain lightweight portable equipment, the antenna can be collapsed completely into the equipment itself so that none of it is exposed.

c. Sometimes a whip antenna mounted on a vehicle must be left fully extended so that it can be used instantly while the vehicle is in motion. In such antennas, the base mounting insulator of the whip is fitted with a coil spring attached to a mounting bracket on the vehicle. The spring base allows the whip antenna to be held in a nearly horizontal position by insulated guy lines so that the vehicle can be driven under low bridges or obstructions, although the radiation produced under these conditions is reduced. Another advantage of the spring base is that even if the antenna is vertical and it does hit an obstruction, the whip usually will not break or be bent since most of the bending occurs at the spring base.

d. One common mobile radio station installed in a 2½-ton, 6 by 6 cargo truck uses three such whip antennas—two 15-foot whips for receiving and a single 25-foot whip for transmitting: The truck chassis is used as a ground.

e. When whip antennas are operated in the high-frequency range, their length usually is a small fraction of a wavelength. Here, large loading coils must be used to resonate the whip antenna properly. The radiation resistance of a short whip

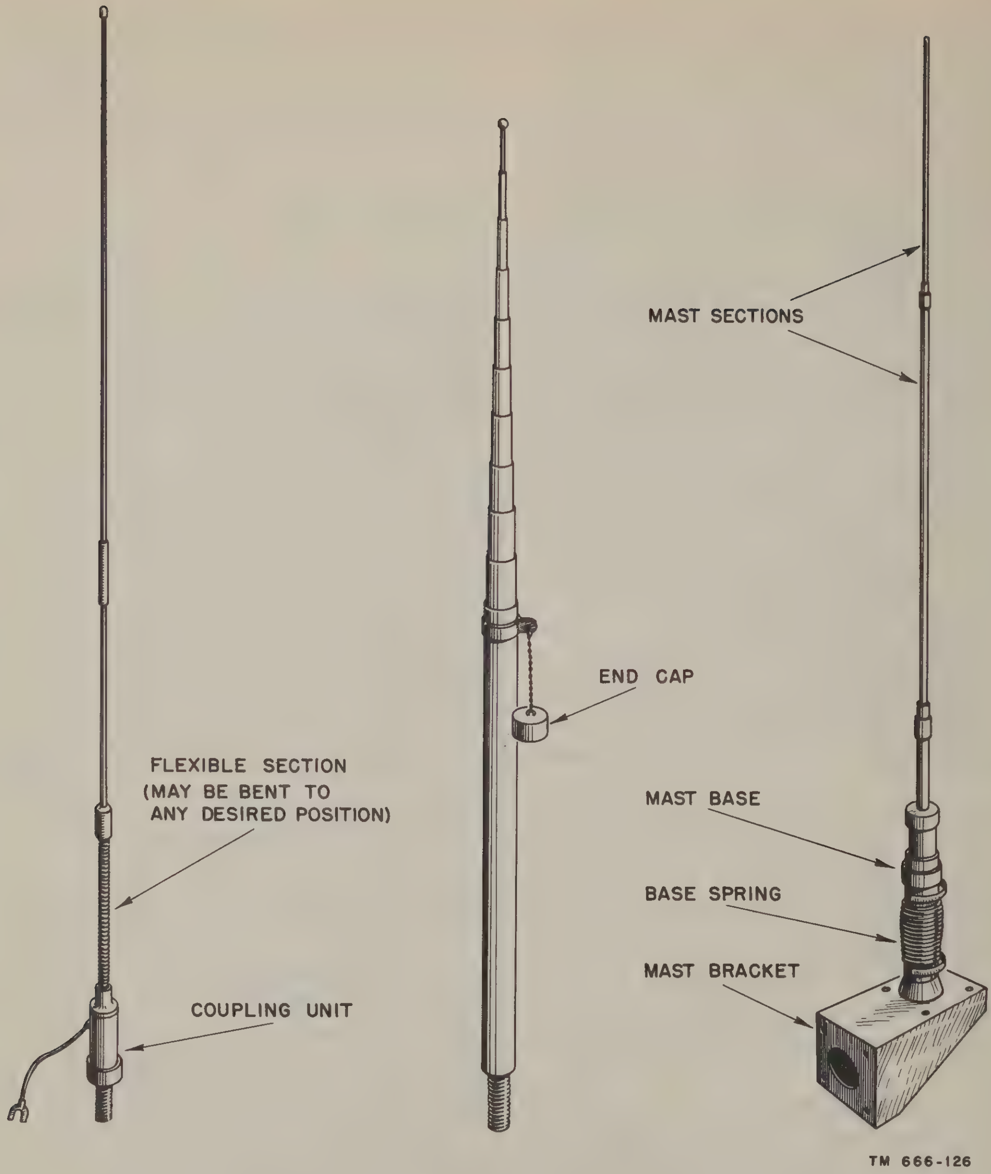

Figure 122. Typical whip antennas.

is very low and it is quite possible that the ohmic losses which result from the resistance of the loading coil, antenna connection, and the antenna itself may exceed the radiation resistance. The radiation efficiency of this antenna is low, being approximately 0.5 to 2 percent in the low end of the high-frequency range. If large whips or even higher frequencies are used, so that the whip length is a quarter- or half-wave, the output of the whip antenna is raised. A 25-foot whip, for example, is a half-wavelength long at about 18.5 mc.

f. In the very-high-frequency band (and higher) short whip antennas can be a quarter- or a half-wavelength long. For example, a 4-foot whip is a quarter-wavelength long at about 60 mc and a half-wavelength long at about 120 mc. Under these conditions high radiation efficiencies are possible.

80. Summary

a. The presence of an electric field about an antenna indicates the presence of a voltage on the antenna, resulting from the charge placed on the antenna by the transmitter.

b. The presence of a magnetic field about an antenna indicates the presence of a current in the antenna. This current is the charge moving in the antenna.

c. The electric and magnetic fields that immediately surround an antenna, forming the induction field, are in space and time quadrature.

d. Standing waves on an antenna are the result of incident and reflected traveling waves moving in opposite directions on the same conductor.

e. The standing wave of voltages on a half-wave antenna is so distributed that it has maximum amplitude at the antenna ends and minimum amplitude at the center of the antenna.

f. The standing wave of current on a half-wave antenna is so distributed that it has maximum amplitude at the center of the antenna and minimum amplitude at the antenna ends.

g. The velocity of wave travel on an antenna is lower than in free space. As a result, the physical length of a half-wave antenna is about 5 percent shorter than its electrical length.

h. A current flowing in an antenna must contend with radiation resistance, ohmic resistance, and leakage resistance.

i. In the half-wave antenna, the radiation resistance is large compared to the other resistances, so that most of the available energy is radiated.

j. If an antenna is cut to a length of exact resonance, the reactance is zero and the impedance of the antenna is purely resistive. If the antenna is made somewhat shorter, capacitive reactance is present; if the antenna is made longer, inductive reactance is present.

k. A transmission line is a device for guiding electrical energy from one point to another. Such a line has electrical constants of inductance, capacitance, and resistance distributed along its length.

l. A line terminated in a resistance equal to its characteristic impedance is said to be terminated properly.

m. The ratio of maximum to minimum voltage along a transmission line is called the standing-wave ratio. This ratio provides a measure of the energy reflected.

n. A properly matched line is nonresonant. It produces no reflection of energy and there are no standing waves. As a result, there is maximum transmission of energy.

o. A resonant line is terminated in a load not the same as Z_o. This line has standing waves so that the standing-wave ratio is greater than 1. Such a line, when cut to certain lengths, exhibits the properties of a resonant circuit.

p. The transmission line used to couple the transmitter to the antenna sometimes is called a feeder.

q. In determining how to connect a feeder line to the antenna, it is necessary to consider the antenna impedance at the connection point and the type of antenna that is used.

r. A single-wire transmission line must be connected to a suitable point on the antenna between the end and the center in order to effect an impedance match. Two-wire and other lines usually are connected at the center or at the end of the antenna.

s. A delta-matching section used with a two-wire line is made by fanning out the end of the transmission line as it approaches the antenna.

t. *T*-matching and *J*-matching are two commonly used impedance-matching systems with two-wire feeders.

u. Stub matching, which utilizes sections of transmission line, frequently is used to connect a nonresonant feeder line to an antenna.

v. The radiation pattern is a measure of the energy radiated from an antenna taken at various angles and at a constant distance from the antenna.

w. Most radiation patterns are plotted in polar coordinates. This system of graphing has the advantage over the rectangular coordinate graph in that positions are indicated on the graph which are directly related to the actual positions at which measurements are taken around an antenna.

x. The radiation pattern of a dipole is circular in a plane at right angles to the antenna. Broadside, the pattern resembles a somewhat flattened figure 8.

y. The beam width is measured between the points where the field strength falls off to 0.707 of maximum, or where the power falls off to 0.5 of maximum.

z. The presence of ground beneath an antenna affects the radiation pattern.

aa. The energy received at a distant point is the sum of the direct wave and the ground-reflected wave.

ab. The reflection factor is a term by which the free-space radiation pattern of an antenna must be multiplied in order to determine the radiated field strength of a practical antenna at a given vertical angle.

ac. In general, ground reflections result in the breaking up of the vertical-plane radiation pattern into a number of separate lobes.

ad. The radiation resistance of a practical, half-wave antenna located over a ground plane may have any value of radiation resistance from 0 to almost 100 ohms, depending on the exact height.

ae. Because the ground has resistance and is not a perfect reflector, a portion of the wave which ordinarily would be reflected is absorbed in the ground resistance. This absorption constitutes ground losses.

af. With an imperfectly conducting ground, the vertical radiation pattern shows a series of high and low signal strengths rather than a series of double-amplitude lobes separated by well defined nulls.

ag. A ground screen can be used to establish accurately the location of the reflecting ground plane and to minimize ground losses. The ground screen consists of a fairly large area of metal mesh or screen which is laid on the surface of the ground under the antenna.

ah. The polarization of a radio wave is determined by the direction of the electric flux lines with respect to the surface of the earth.

ai. In general, the characteristics of an antenna used for transmitting are much the same as when the antenna is used for receiving. The antenna receives best in those directions in which it radiates best.

aj. A single-wire, half-wave antenna is one which is constructed of a single conductor of proper length.

ak. The folded-dipole antenna consists of an ordinary, half-wave antenna which has one or more additional conductors connected across the ends of the antenna. These are mounted parallel to the dipole elements at a distance that is a very small fraction of a wavelength.

al. A coaxial or sleeve antenna consists of a quarter-wave vertical radiator with a quarter-wave sleeve that fits around the antenna support mounted just below it. The sleeve acts as the lower portion of the antenna.

am. The conical antenna is a wide-band antenna whose elements are constructed in the form of cones.

an. A quarter-wave antenna which operates in conjunction with ground operates as a resonant antenna.

ao. The current in a quarter-wave, grounded antenna is maximum at the grounded end and the voltage is a minimum. The impedance of such an antenna is minimum at the grounded end.

ap. The radiation resistance of a grounded, quarter-wave antenna is about 36 ohms. Shorter antennas have lower radiation resistance.

aq. Loading coils are used frequently to increase the electrical length of short, grounded, quarter-wave antennas.

ar. Maximum radiation from a grounded, quarter-wave antenna occurs at right angles to the antenna and along the surface of the ground. No radiation occurs directly over the antenna.

as. With grounded antennas, it is especially important that the ground connection be good and that the ground conductivity is high.

at. Large, underground, radial grounds are common for fixed-station installations. Ground rods also are useful in providing good ground connection.

au. A counterpoise is utilized when an actual ground connection cannot be used because of the high resistance of the soil or because a large buried ground system is not practical.

av. A bent antenna is a grounded antenna which is constructed so that a portion of it is horizontally mounted.

aw. The advantages of a bent antenna are the reduction in high-angle radiation and an increase in the amount of radiation produced.

ax. A folded-top antenna is a modified bent antenna in which the flattop is folded in such a way that it prevents radiation.

ay. Top-loading increases the electrical length of the antenna. When top-loading is used, the radiation resistance of the antenna is increased and the radiation efficiency of the antenna rises.

az. Metal masts and towers can be used as grounded vertical radiators. These are either self-supporting or guyed, insulated or noninsulated.

ba. A ground-plane antenna consists of a quarter-wave vertical radiator which carries its own ground consisting of a flat, metal disk or a number

of metal rods or spokes located at the bottom of the radiator and at right angles to it.

bb. The whip antenna, which is a short, flexible, vertical radiator, is the most common antenna used for tactical radio communication when short distances are to be covered.

81. Review Questions

a. What is the direction of the electric flux lines that surround an antenna?

b. What is responsible for the magnetic field that surrounds an antenna?

c. Explain the expression, *space and time quadrature*.

d. What is meant by a *loop*, a *node*?

e. Describe the distribution of the standing waves of voltage and current along a half-wave antenna.

f. Give several factors that cause the velocity of wave travel on an antenna to be lower than in free space.

g. What is the free-space length (in feet) of a half-wave at a frequency of 7 mc?

h. How long is a half-wave antenna which is to operate at 7 mc?

i. What causes radiation resistance? Ohmic resistance? Dielectric resistance?

j. What is the value of the radiation resistance as measured at the center of a half-wave antenna?

k. Why is it important to minimize the reactance seen by a transmission line that is connected to an antenna?

l. What is the purpose of a transmission line?

m. Why is it advantageous to terminate a transmission line properly?

n. Give three methods by which transmission lines dissipate power.

o. Describe the current and voltage distribution on closed-end lines. On open-end lines.

p. How does the standing-wave ratio indicate the amount of line mismatch?

q. What is the purpose of an impedance-matching device?

r. Describe several types of practical transmission lines.

s. What is a tuned line? An untuned line?

t. What lengths of open-end, resonant, transmission line are required to cause the line to act as an impedance transformer?

u. Where is a current-fed, half-wave antenna fed?

v. If voltage feeding is required, where should the feeders be connected to the half-wave antenna?

w. Give some advantages and disadvantages of the single-wire feeder.

x. Give some advantages and disadvantages of the delta-matching system.

y. What are some characteristics of the T-matching system?

z. Describe the J-matching system.

aa. Give several examples of impedance matching by the use of stubs.

ab. Describe the Q-matching system.

ac. What is an isotropic radiator? Give an example.

ad. What constitutes a lobe on a radiation pattern? A null?

ae. Do radiation patterns actually picture the radiation produced by an antenna?

af. Distinguish between a dipole and a doublet as used in this section.

ag. Why does the presence of ground beneath the antenna affect the radiation pattern?

ah. What is meant by an image antenna?

ai. What are the minimum and maximum values of reflection factor?

aj. What determines the value of the reflection factor?

ak. Describe the vertical-plane radiation pattern produced by a horizontal half-wave antenna when its height above ground is increased gradually.

al. Why does the radiation resistance of an antenna change at differing heights above ground?

am. How does the frequency of the radiation from an antenna affect the amount of ground losses?

an. What effect does an imperfect ground have on the radiation resistance of an antenna?

ao. Give two specific advantages that are gained by the use of a ground screen.

ap. How does the orientation of an antenna affect the polarization of the radiation produced?

aq. Give some advantages of horizontal polarization.

ar. Give some advantages of vertical polarization.

as. What is meant by the reciprocity of an antenna?

at. What is the input impedance of a folded dipole antenna?

au. Explain the greater bandwidth of the folded dipole.

av. What is the function of the sleeve or skirt on the coaxial antenna?

aw. What are the characteristics of a coaxial antenna?

ax. Describe some simple microwave antennas.

ay. What is a Marconi antenna?

az. What is the current and voltage distribution on a grounded, quarter-wave antenna?

ba. What is the function of a loading coil?

bb. Describe the radiation pattern produced by a vertical, half-wave antenna.

bc. Compare the radiation resistance of a quarter-wave antenna with an antenna that is only a tenth-wavelength long.

bd. Describe a radial ground.

be. What is the purpose of a ground rod, and how does chemical treatment affect the operation of a ground rod?

bf. For what purpose is a counterpoise used?

bg. When are bent antennas used?

bh. What lengths are desirable for the flattop in a bent antenna?

bi. Why do low-frequency, bent antennas use flattops constructed of several connected conductors?

bj. What is the crowfoot antenna?

bk. Why is it advantageous to minimize radiation from the flattop of an antenna?

bl. Describe some devices commonly used for top-loading an antenna.

bm. Distinguish between an insulated and a noninsulated tower.

bn. When is a tower radiator series-fed? Shunt-fed?

bo. What is the radiation pattern produced by a ground-plane antenna?

bp. What advantages occur when the rods forming the elevated ground plane in a ground-plane antenna are bent downward below the horizontal?

bq. Why do some whip antennas have spring bases?

CHAPTER 4

LONG-WIRE ANTENNAS

82. Introduction

Long-wire antennas are long single wires, longer than 1 half-wavelength, in which the current in adjacent half-wave sections flows in opposite directions. Such antennas have two basic advantages over the antennas discussed in the previous chapters. These advantages are increased *gain* and *directivity*.

a. Antenna Gain.

(1) All of the antennas discussed so far have been basic half- and quarter-wave antennas that radiate equally in all directions. Greatest amounts of power are radiated in directions that are broadside to the antenna itself, and very little power is radiated off the antenna ends. Consequently, the basic antennas already discussed have a certain degree of *directivity*, which is *the ability to radiate and receive energy better in some directions than in others.*

(2) An *isotropic* antenna is one that radiates equally in *all* directions. In actual practice, every antenna radiates more energy in certain directions than in others. The imaginary isotropic antenna, however, can be used only as a standard for comparison.

(3) Assume that a certain amount of power is applied to an isotropic radiator. This produces a field having a certain strength at a distant receiving antenna. If the same amount of power is applied to a half-wave antenna that is far removed from ground, this antenna will produce a field the strength of which is greater in certain directions than that produced by the isotropic radiator. This increase in field strength in some directions can be produced only at the expense of field strength in other directions; that is, an increase in field strength in certain directions must be accompanied by a decrease in field strength in other directions. As a result, a distant receiving antenna will have a greater or lesser amount of induced voltage depending on its position with respect to the orientation of the radiating antenna. The half-wave antenna produces an increase or *gain* in field strength in the direction at right angles to itself, and a decrease or *loss* in field strength in other directions. In the direction of maximum radiation, the antenna produces an increased field strength (field strength gain) that is about 1.28 times that produced by the isotropic radiator. This is equivalent to an increase in power (power gain) of 1.64 times that obtained from the isotropic radiator. In other words, if the power applied to the isotropic radiator were increased 1.64 times, exactly the same field strength would be produced for all directions as is obtained from the basic half-wave antenna in the direction of maximum radiation.

(4) Gain frequently is expressed in terms of the logarithmic ratio, the decibel. In order to convert the figures to decibels, it is necessary only to use the formulas below:

$$\text{Gain (in db)} = 20 \log_{10} \text{x field-strength ratio}$$
$$\text{Gain (in db)} = 10 \log_{10} \text{x power ratio.}$$

When either or both of these formulas are solved, it is found that the gain of the basic half-wave antenna is 2.15 db over that of the isotropic radiator.

b. Calculation of Gain.

(1) Since no antenna is truly isotropic, it is common practice to use a basic half-wave antenna as a standard for reference. The reference field strength is the field intensity at a fixed point produced by the half-wave antenna in the direction of

its maximum radiation. The reference power is the power applied to the standard antenna. If any antenna produces a greater field strength at the same fixed point than does the standard antenna, it is said to have *gain* with respect to the standard. Conversely, if the antenna produces less field strength at the fixed point than does the standard antenna, it is said to have *loss* with respect to the standard.

(2) In actual practice, the procedure is first to set up the antenna to be checked. A given amount of input power is applied and the field strength is measured at a distant receiving point. Then, the half-wave antenna is set up at the same position and height above the earth, and oriented so that a field having the same polarization as the original antenna is produced. Exactly the same power is applied to the half-wave antenna as was applied to the other antenna. The field strength then is measured at the same distant receiving point. Comparison between the two field strengths indicates whether the antenna being checked produces a gain or a loss in field strength compared with the reference antenna.

(3) Another method used to measure the gain (or loss) of an antenna involves an actual measurement of the input power to the antenna. The amount of input power applied to the antenna to be checked is measured, the field strength at a certain distant point is noted, and the half-wave antenna is set up as in the preceding method. The power applied to this reference antenna then is adjusted until exactly the same field strength is produced at the distant point. If *more* power must be applied to the reference antenna to produce the same field strength at the point as produced by the antenna under test, the antenna under test has a *gain* with respect to the reference antenna. On the other hand, if *less* power must be applied to the half-wave reference antenna to produce the same field strength, the antenna under test has a *loss* with respect to the reference antenna. The ratio between the two input powers (reference antennas divided by tested antennas) gives the gain (or loss) of the antenna being tested. Because an accurate measurement of different field strengths cannot be made as easily as an accurate measurement of different antenna input powers, this method is preferred to that described in (2) above.

(4) If the antenna under test produces the same field strength at a certain distance with exactly the same power applied as is produced by the reference half-wave antenna, there is neither a gain nor a loss. The ratio between the two input powers is unity (1 to 1) as is the ratio between the two field strengths with the same input power. Since the logarithm of 1 is zero, the gain in decibels as calculated by the formulas previously given is 0 db. This is simply another way of saying that there is neither a gain nor a loss. The reference level of field strength produced by the half-wave antenna, or a level equal to the reference level, is referred to as the *zero db level*. The standard half-wave antenna which produces the reference field strength often is referred to as the *zero db antenna*.

(5) If a certain antenna has a gain of 10 db, it produces a field strength that is over three times greater than that produced by the half-wave antenna with the same input power. This same antenna produces the same field strength as that produced by the half-wave antenna when the power applied to the half-wave antenna is 10 times greater than that applied to the antenna under test. The chart given below gives the db gain or loss for various field strength and power ratios.

Db gain or loss	Field-strength ratio	Power ratio
0	1. 0	1. 0
1	1. 12	1. 26
2	1. 26	1. 56
3	1. 41	1. 99
4. 5	1. 68	2. 82
6	1. 99	3. 98
8	2. 51	6. 31
10	3. 16	10. 0
12. 5	4. 22	17. 8
15	5. 62	31. 6
20	10. 0	100. 0
30	31. 6	1, 000. 0
40	100. 0	10, 000. 0

c. Directivity.

(1) Since all antennas are directional to a certain degree, the term *directional* usually is applied only to those antennas that are rather highly directional. The main advantage to be gained from the use of the long-wire antennas and arrays is in their greater directional qualities. These antennas all concentrate a larger amount of the available radiated energy into a smaller sector.

(2) Some antennas are directional in some planes but practically nondirectional in others. Consider, for example, the basic half-wave antenna that is mounted in a vertical position. If a vertical plane is passed through the center of the antenna and the radiation pattern is drawn on that plane, the pattern would take the form of a figure 8. Maximum radiation occurs in the two directions that are at right angles to the antenna itself and no radiation occurs off the ends. The antenna is said to have two lobes of radiated energy and two nulls. Consequently, this antenna is said to be bidirectional (it radiates in two directions) in the vertical plane. If the horizontal plane is considered, however, it is seen that the antenna radiates equally in all directions. The antenna therefore is nondirectional in the horizontal plane. When highly directional antennas are used, it is important to know in which plane the desired directivity occurs.

(3) Highly directional antennas are designed to produce a large increase in radiated (or received) energy in one direction. The idea, however, may be to prevent radiation (or reception) in a certain direction. For example, assume that two powerful transmitters are located near each other. To prevent these transmitters from interfering with each other, it is necessary to use directional antennas with respective nulls pointing toward each other. Under these conditions, the antennas may be adjusted to produce the least amount of radiated energy in the direction of each other, rather than the greatest amount of energy in any given direction.

83. General Characteristics of Long-wire Antennas

a. If the length of a long-wire antenna is such that two or more half-waves of energy are distributed along it, it often is referred to as a harmonic antenna. Consider the half-wave antenna shown in *A* of figure 123. At a given instant, the polarity of the r-f generator connected to the center of the antenna is positive at its left-hand terminal and negative at its right-hand terminal. As a result, current in the left half of the antenna flows toward the generator, whereas current in the right half of the antenna flows away from the generator. In both halves of the half-wave antenna, current flows in the same direction, from left to right, as shown by the wave of current *above* the antenna wire.

b. Now assume that the antenna just discussed is increased until it is 2 half-wavelengths, as in *B*. With the r-f generator still connected at the center and with the same instantaneous polarities as in *A*, current in the left side of the antenna must flow toward the generator, and current in the right side must flow away from the generator. Since the antenna is now 2 half-wavelengths, 2 half-waves of current can be accommodated on the antenna and the current polarity is the same in both halves of the antenna. It is important to note that this is *not* a true long-wire or harmonically operated antenna since there is no reversal of current flow in adjacent half-wave sections. Instead, this arrangement is simply 2 half-wave antennas operating in phase at their fundamental frequency. Such an arrangement is called a driven collinear array (paragraphs 94 through 109)

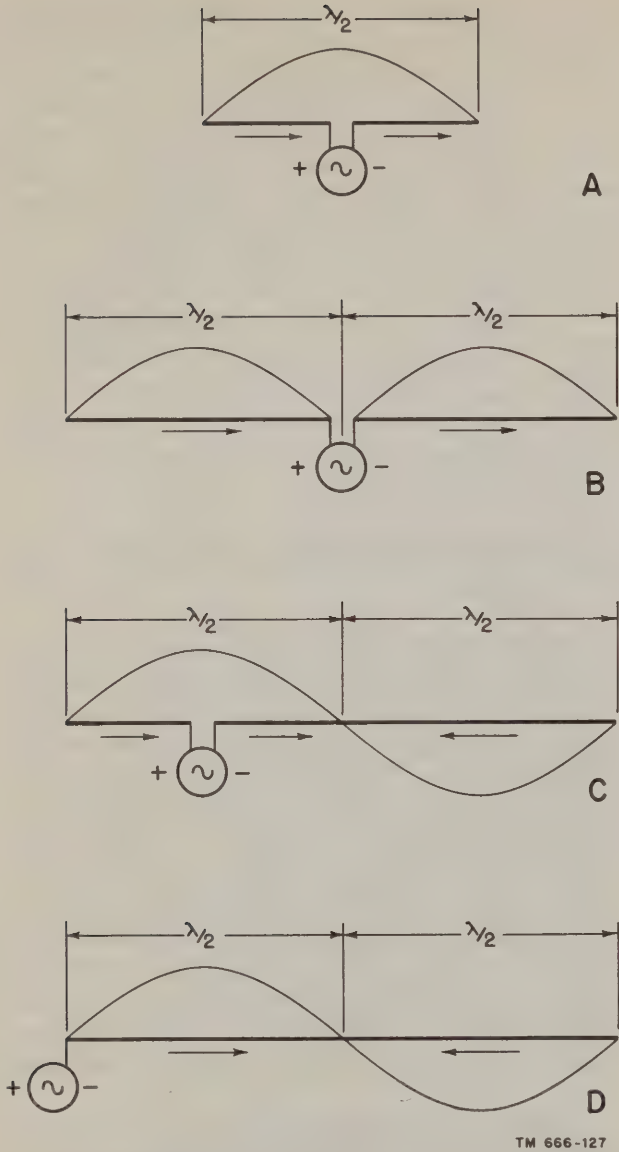

Figure 123. Harmonic and nonharmonic antennas.

and has characteristics quite different from those to be discussed for the true harmonically operated or long-wire antenna.

c. The antenna in *B* can be converted into a true long-wire, harmonically operated antenna simply by moving the generator to a current loop as shown in *C*. With the r-f generator polarity as shown, current flows from left to right in the half-wave section of the antenna. The direction of current flow then is reversed in the second half-wave section. If the generator is moved to the extreme end of the antenna as shown in *D*, the antenna is also a long-wire antenna, and the current distribution on the antenna is exactly the same as in *C*.

d. The harmonically operated antenna, therefore, must be fed either at a current loop or at its end for proper operation. If the antenna is any odd number of half-wave lengths (1½, 2½, 3½, and so on) so that a current loop occurs at the center of the antenna, center feeding can be used.

e. As the length of an antenna is increased, it is natural to expect a change in the radiation pattern produced by the antenna. A long-wire antenna can be considered to be one made up of a number of half-wave sections fed 180° out of phase and spaced a half-wavelength apart. As a result, there is no longer zero radiation off the ends of the antenna, but considerable radiation occurs in the direction of the long wire as a result of the combined fields produced by the individual half-wave sections. In addition, radiation also occurs broadside to the long wire. Consequently, the resultant maximum radiation is neither completely at right angles to the long wire nor completely along the line of the long wire. Instead, the maximum radiation occurs at some acute angle in respect to the wire, the exact angle being determined by the length of the antenna.

f. It will be shown that as the length of a long-wire antenna is increased, the following characteristic changes occur: First, the gain of the antenna increases considerably compared with that of the basic half-wave antenna, especially when the long wire is many wavelengths. Second, the direction along which maximum radiation occurs makes a smaller angle with respect to the wire itself. Consequently, as the antenna is made longer, its major lobe of radiation lies closer to the direction of the wire itself. Third, more minor lobes are produced as the antenna length is increased.

84. Harmonically Operated Antennas in Free Space

a. Calculation of Length.

(1) It already has been pointed out (pars. 36 through 81) that the electrical and physical lengths of a half-wave antenna are not the same because of the reduction in wave velocity on the antenna resulting from its thickness and because of end effect. The main factor producing end effect is the use of insulators at the antenna ends. These introduce additional capacitances to the antenna which lower its resonant frequency and increase the electrical

length of the antenna. Consequently, the half-wave antenna is foreshortened by 5 percent to compensate for these effects.

(2) Since, in a long-wire antenna, the insulators are used at the ends and not between adjacent half-wave sections, it is only the half-wave sections at the antenna ends that are affected by end effects. Therefore, a harmonically operated antenna of 1 wavelength is foreshortened by only 2½ percent over-all, one of 2 wavelengths is foreshortened by 1¼ percent over-all, and so on. A convenient formula that is used to determine the length in feet of a harmonic antenna for any given frequency in megacycles is

$$\text{length} = \frac{492\,(H-0.05)}{\text{frequency}}$$

where H is the number of *half*-waves on the antenna.

(3) Note that the foreshortening of the long-wire antenna is less than for the simple half-wave antenna. For this reason, a long-wire antenna with, say, 3 half-waves on it is slightly longer than three times the length of a half-wave antenna. Therefore, the length of the half-wave antenna is not an exact submultiple of the length of the harmonic antenna.

b. Standing Waves and Impedances at Various Frequencies.

(1) As the length of the antenna is increased so that it operates on higher harmonic frequencies, or, as the frequency applied to an antenna of fixed length is raised, a greater number of half-waves of voltage and current occur on the antenna. This is shown in figure 124, where antennas operating on the second, third, fourth, and fifth harmonics appear. The standing waves of voltage and current are 90° out of phase.

(2) The impedance of the harmonic antenna at any point is determined by the reactance and the resistance of the antenna at that point. The impedance often is measured at a current loop, because this is where the feed line usually is attached. When the antenna length is such that exact harmonic resonance occurs or if the reactance is tuned out otherwise, only resistance remains. This resistance is largely radiation resistance, since the ohmic losses of the antenna usually are so low that they can be neglected compared with the value of radiation resistance.

(3) The following chart shows the approximate radiation resistance, measured at a current loop, of harmonic antennas of various lengths. As the antenna length

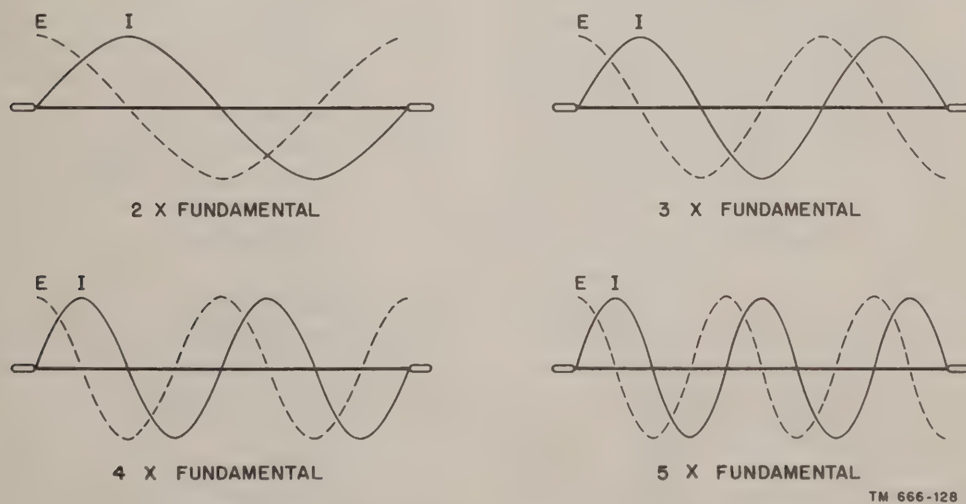

Figure 124. *Standing waves on harmonic antennas.*

Antenna length (wavelengths)	Radiation resistance (ohms)	Antenna length (wavelengths)	Radiation resistance (ohms)
1	90	5	138
1½	100	6	144
2	110	8	154
2½	117	10	162
3	122	13	170
4	130		

is increased, the value of radiation resistance also increases.

(4) When the frequency applied to an antenna is no longer the resonant frequency, a considerable reactive component is present. Consider a half-wave antenna that is fed at the center. As the frequency of the r-f generator is increased above the resonant frequency of the antenna, the antenna becomes inductive with an inductive reactance. This inductive reactance reaches a maximum value and then begins to fall off as the frequency is raised still more. When the frequency is such that the antenna length is slightly less than a full wavelength, the reactance is zero. An increase in frequency above this value causes the antenna to behave as a capacitive reactance. As the frequency is raised still higher, the capacitive reactance reaches a maximum value and then falls off toward zero. When the frequency is such that the antenna is slightly less than 1½ wavelengths, the reactance again is zero. An increase in frequency above this value causes the antenna to behave as a inductive reactance. As the frequency is raised still higher, the inductive reactance reaches a maximum value and then falls off toward zero. When the frequency is such that the antenna is slightly less than 2 wavelengths, the reactance again is zero. An increase in frequency above this value causes the antenna to behave as a capacitance once more. Consequently, a complete cycle of reactance changes occurs as the frequency is increased so that electrically the antenna is changed from a half-wavelength to 1½ wavelengths. A similar cycle occurs as the antenna is changed from 1½ to 2½ wavelengths, from 2½ to 3½ wavelengths, and so on.

(5) During the time the reactance is going through a cycle, the resistive component of the impedance also varies with the change in frequency. It is at a minimum value when the frequency is such that the antenna is about a half-wavelength and reaches a maximum value when the antenna is about 1 wavelength, and back to a minimum value when the antenna length is approximately 1½ wavelength. These cyclic variations in reactance and resistance are shown in figure 125. As a result of these variations, the impedance of the antenna also has a cyclic variation as the frequency is raised from one harmonic to another.

(6) The rate at which the impedance varies is increased at the higher frequencies. The impedance at the center of an antenna varies from minimum to maximum when the frequency applied increases from the fundamental to the second harmonic. A similar variation must take place when the frequency applied increases from the fifth to the sixth harmonic. From the fundamental to the second harmonic, however, a frequency increase of 100 percent occurs, and from the fifth to the sixth harmonic, there is a frequency increase of only 20 percent. Therefore, the impedance must change five times faster in the vicinity of the fifth harmonic than in the vicinity of the fundamental.

(7) As the frequency applied to a given antenna or as the length of an antenna is increased, the resistive component of its impedance rises, and as the radiation resistance of an antenna rises, the length and losses increase. As a result, as the antenna varies from a half-wavelength to 1½ wavelengths, and the resistance does not drop to as low a value at 1½ wavelengths as at a half-wavelength, nor does it rise to as high a value at 2 wavelengths as at 1 wavelength (fig. 125). This is true also as the frequency increases to 5, 6, or more times the fundamental, or as the antenna increases to 3 wavelengths, 4 wavelengths, and so on.

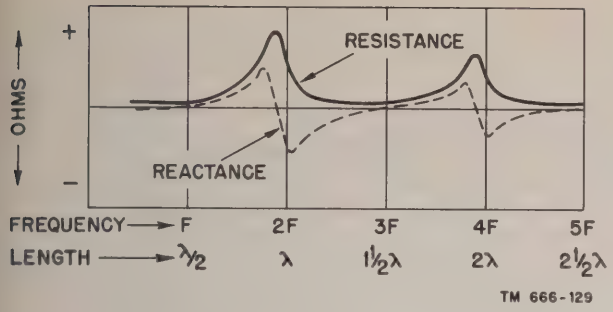

Figure 125. Cyclic variations of reactance and resistance at center of antenna.

Although cyclic changes in impedance still occur at long antenna lengths or at high applied frequencies, the impedance does not rise to as high a value nor does it fall to as low a value as occurs at low harmonic frequencies or short antenna lengths.

c. Directivity and Gain.

(1) The maximum radiation from a harmonic antenna forms a lobe which covers a smaller and smaller sector as the antenna length is increased. Since a greater amount of power is concentrated into a smaller sector, the harmonic antenna has a power gain with respect to the half-wave antenna.

(2) The approximate power gain of harmonic antennas of various lengths is shown in the following chart:

Antenna length (wavelengths)	Power gain	Antenna length (wavelengths)	Power gain
1	1. 2	8	4. 3
2	1. 4	10	5. 6
4	2. 1	12	7. 2
6	3. 1		

(3) Very little gain occurs when the antenna is only a few wavelengths. When the length becomes appreciable, however, considerable power gains result, and increased power gain is accompanied by greater directivity. This is true since an increase of power in certain directions is attained by reduction of power in other directions.

(4) The radiation produced by a harmonic antenna is neither completely at right angles to the antenna itself nor off the ends of the antenna. Instead, the maximum radiation forms lobes which lie closer and closer to the direction of the antenna itself as the length of the antenna increases. The angle of maximum radiation is the angle between the line running through the center of the lobe and the antenna wire.

(5) The approximate angles of maximum radiation for harmonic antennas of various lengths are given in the following chart:

Antenna length (wavelengths)	Angle of maximum radiation (degrees)	Antenna length (wavelengths)	Angle of maximum radiation (degrees)
1	54	8	18
2	36	10	17
4	25	12	16
6	20		

d. Radiation Patterns.

(1) Figure 126 shows the radiation patterns of harmonic antennas up to 3 wavelengths. The field strength produced by the half-wave antenna is shown for comparison. Note that as the antenna length is increased, more lobes are produced. The 1½-wavelength antenna, which operates on the third harmonic, has three lobes—two major lobes and one minor lobe, the latter lying at right angles to the antenna. The 3-wavelength antenna, which operates on the sixth harmonic, has six lobes—two major lobes and four minor lobes.

(2) The harmonic antennas which operate on the even harmonics (2d, 4th, and so on) have an even number of half-wave patterns distributed along their length. Since the adjacent half-wave sections have currents of opposite phase, a distant point in space located equidistant from the ends of the antenna is acted on by equal and opposite fields. Cancellation of fields occurs and a null is produced on a plane at right angles to the antenna, cutting it at the center. On the other hand, harmonic antennas which operate on the odd harmonics have an odd number of half-wave sections. Complete cancellation of radiated fields does not

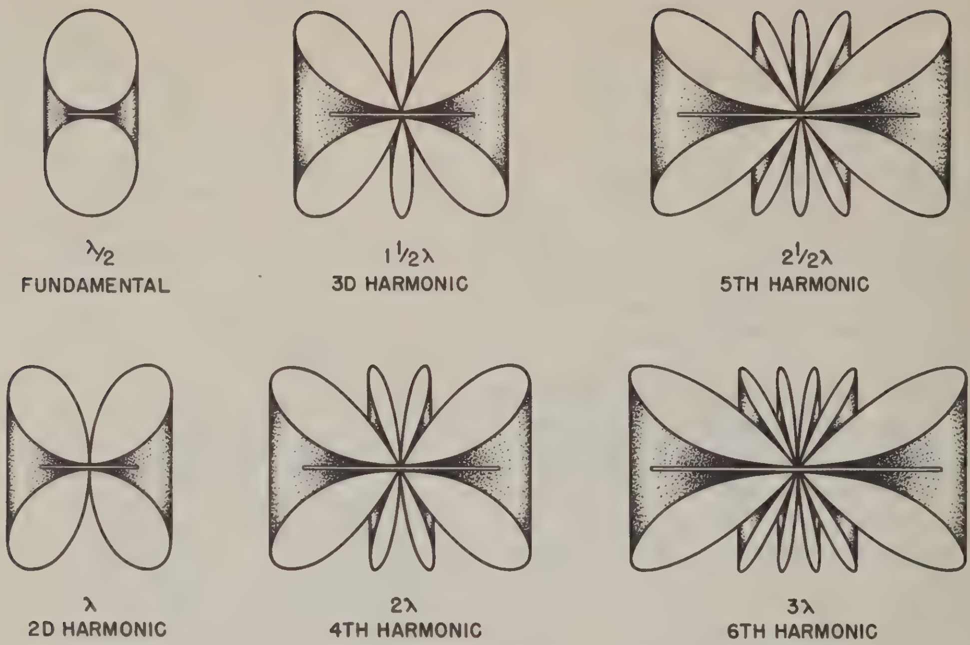

Figure 126. Radiation patterns of harmonic antennas.

occur at points equidistant from the ends of the antenna because of the odd half-wave section. This results in a minor lobe being produced in a direction that is perpendicular to the antenna, and coming from its center.

85. Effects of Ground

a. The radiation patterns of a harmonic antenna are modified considerably by the presence of the earth under the antenna. Some of the energy radiated from the antenna travels downward toward the earth, where it is reflected. If the reflected energy arrives at some distant point in phase with the direct energy from the antenna, then reinforcement of the signal strength occurs. On the other hand, if the reflected energy arrives 180° out of phase with the direct energy, a reduction or cancellation of signal strength takes place.

b. Energy reflected from ground will induce a voltage into the harmonic antenna. This causes a current to flow which combines with the original antenna current. The total antenna current then will be greater or less than the original antenna current, depending on the height of the antenna. Consequently, the radiation resistance of the harmonic antenna varies, depending on the height above ground. In this respect, the behavior of the harmonic antenna is the same as the half-wave antenna.

c. Some horizontal radiation patterns at various vertical angles above harmonic antennas parallel to the ground are shown in figure 127. As the vertical angle is reduced—that is, approaching a horizontal plane which includes the antenna—the pattern resembles those shown previously in figure 126. However, as the vertical angle increases toward the angle of the lobe maximum, the patterns become filled in. The nulls in the direction of the antenna itself disappear.

d. The shapes of the patterns are not altered by the earth. The effect of the earth is to change the relative amplitude of a pattern, which can be seen by comparing the 10° pattern with a 15° pattern, on *A*, *B*, or *C*. It is possible for the maximum lobe which occurs at one vertical angle to be reduced to zero, whereas the maximum lobe which occurs at another vertical angle can be increased to twice its normal free-space value. In order to note the effect of the ground on the radiation pattern, it is necessary to alter the patterns produced at various angles by taking into account the antenna height.

86. Feeding Long-wire Antennas

a. Both resonant and nonresonant lines can be used to feed long-wire antennas. The same

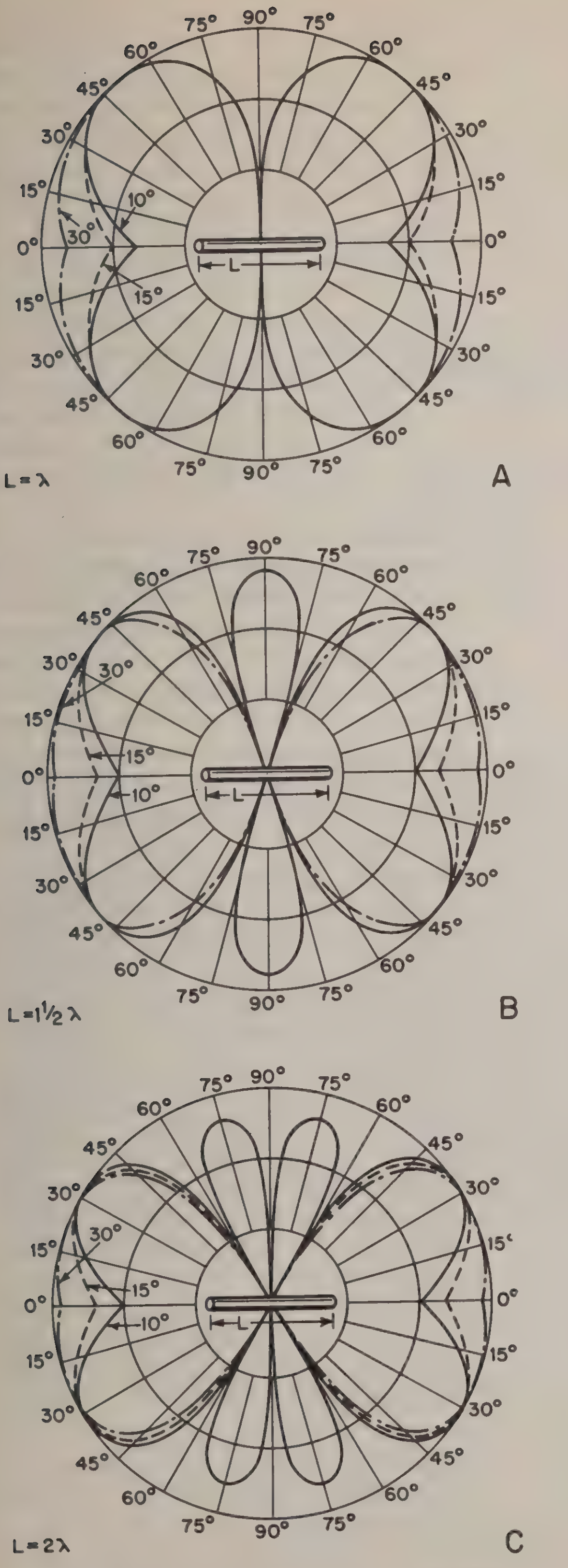

Figure 127. Horizontal patterns of harmonic antennas at various vertical angles.

general principles apply here as in the half-wave antenna. Since a point on the antenna which is a current loop becomes a current node on the next higher harmonic, a current-fed antenna behaves as a true long wire only at odd harmonics of the original frequency. Therefore, for operation on all harmonics, end feeding is preferred. However, with end feeding, unbalanced transmission-line currents result and a nonsymmetrical radiation pattern is produced. The intensity of the lobes in the direction off the feeder end of the long wire is reduced, and the intensity of the lobes in the direction away from the feeder end is increased. When matching sections of line are used with nonresonant feeders, it must be realized that these operate over only a narrow band of frequencies.

b. An end-fed long-wire antenna with a resonant feeder line is shown in figure 128. Operation on all harmonic frequencies is possible with this arrangement, provided the tuning unit at the input end of the resonant line has sufficient range to match the input impedance to the transmitter. Arrangements for using nonresonant lines are shown in *B* and *C*. In both, quarter-wave matching sections are used to match the nonresonant line to the long-wire antenna. In *B*, the feeder is tapped on the matching section at a point where an impedance match occurs.

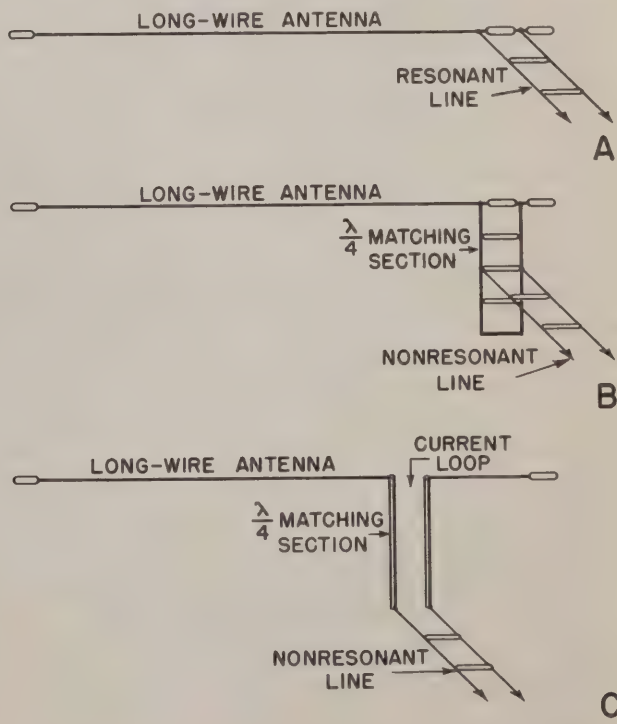

Figure 128. Feeding long-wire antennas.

In *C*, the feeder is connected to a *Q*-matching section the characteristic impedance of which is made equal to the square root of the product of the radiation resistance of the long-wire antenna and the impedance of the nonresonant line.

87. Resonant and Nonresonant Antennas

a. Only resonant antennas have been discussed heretofore in this manual. These have standing waves of voltage and current distributed along their length which are set up by the reflection of waves at the ends of the antenna. If one end of an antenna is terminated in a resistance that is equal to the characteristic impedance of the antenna, waves can travel in one direction only. As a result, no standing waves are set up. Instead, the current and voltage are distributed uniformly along the length of the antenna. Such an antenna is known as a *nonresonant antenna.*

b. The radiation pattern of a nonresonant antenna is quite different from the pattern produced by a resonant antenna. Consider the radiation patterns shown in figure 126. Assume that all these resonant antennas are made nonresonant by connecting a terminating resistor between the right end of each antenna and ground. All of the antennas then radiate only in the direction of the terminating resistor, or toward the right in the figure. The lobes of energy to the left are largely attenuated. Consequently, the major lobe takes the form of a single cone of radiation surrounding the antenna in the direction of the terminating resistor. The antennas are converted from bidirectional types (which produce maximum radiation in two directions) to unidirectional types (which produce maximum radiation in only one direction). If a radiation pattern were drawn to show the radiation at the vertical angle at which maximum radiation occurs, a single major lobe of radiation appears in the direction of the antenna itself and toward the terminating resistor.

c. An important characteristic of a nonresonant antenna is that it radiates efficiently over a very wide frequency range. Therefore, it is not necessary to cut the antenna for any exact length so long as it is at least several wavelengths.

88. Beverage or Wave Antennas

a. Description and Design.

(1) One type of nonresonant, long-wire antenna is the Beverage or wave antenna which consists of a single wire preferably of 2 or more wavelengths, parallel with the earth and supported on poles at a height of 10 to 20 feet above ground. The far end of the wire is connected to ground through a noninductive resistor of about 500 ohms. This resistor must be able to dissipate about one-third of the power fed into the antenna. This is about the characteristic impedance of a single-wire transmission line with a ground return. A *wave antenna* is shown in figure 129. A reasonably good ground, such as a number of ground rods or a counterpoise, should be used at both ends of the antenna.

(2) Sometimes two or more antenna wires are used in parallel instead of a single wire. This reduces the characteristic impedance of the antenna and ground-return circuit and permits a lower value of terminating resistance to be used. The input impedance of the antenna is reasonably constant with frequency, and the antenna may be used over a wide frequency range without changing its length.

(3) The wave antenna is directional and is used primarily for either transmitting or receiving low-frequency signals. Maximum reception or radiation is in line with the wire and off the terminated end. There is a minimum of radiation in the opposite direction if the antenna is terminated properly. The forward lobe may be made narrower and the gain increased by using a longer antenna wire. However, if extremely long-wave antennas are used, the forward gain falls off.

(4) At frequencies below 800 kilocycles, a properly located wave antenna should give results equivalent to a vertical antenna several hundred feet high. One particular military wave antenna (fig. 130) consists of three conductors arranged in the form of an equilateral triangle 5 feet on a side, erected about 15 feet above ground on short telephone poles, and usually of 2 wavelengths. At a frequency of 500 kilocycles, such an antenna would be almost 4,000 feet long. If ground space limitations prevent the

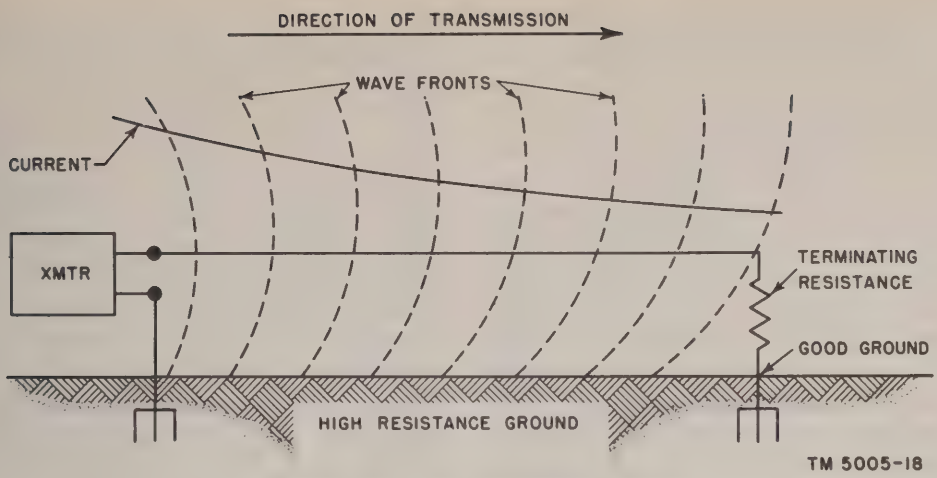

Figure 129. Beverage or wave antenna.

use of such a long antenna, an antenna under 1 wavelength can be used. A reduction of forward gain will result under these conditions.

b. Wave Tilt.

(1) The operation of the wave antenna depends on a process known as wave tilt. When a vertically polarized radio wave travels over the surface of an imperfect conductor, such as the earth, the wave fronts lean forward in the direction of propagation. This is caused by the

Figure 130. Three-wire wave antenna.

slower propagation constant of the earth. The amount of forward tilt depends on the frequency of the r-f wave and the characteristics of the surface over which the wave is traveling. At the lower frequencies at which the wave antenna is used, the wave tilt is approximately proportional to the square root of the product of frequency and soil resistivity. As the resistance of the surface is increased, the wave travel along the surface is reduced and a greater wave tilt results. Consequently, over rocky and sandy soil, a considerable forward tilt results, whereas over salt marshes and sea water, almost no tilt occurs. This means that wave antennas, which depend on wave tilt for proper operation, should not be installed over highly conducting surfaces, but, instead, should be installed only over poor or medium soil. Wave antennas also give good results when installed over ground which has a permanent layer of ice (such as permafrost) a short distance below the surface, or over certain types of ground found in northern or polar regions which are very moist in the summer and have poor conductivity because of lack of mineral content. Actually, it is the average ground conductivity for a considerable distance below the surface that is important rather than the character of a thin top-soil layer.

(2) The wave antenna operates in conjunction with ground, so that a vertically polarized radio wave is radiated. However, because of the forward wave tilt, there is a horizontal component of the electrical field. The vertical and horizontal components are not exactly in phase, and the resultant polarization of the radiated wave, therefore, is elliptical. The wave is radiated in the direction of the tilt which is off the end of the antenna that is terminated in the resistance load.

c. Transmitting Antennas. When the wave antenna is used for transmitting, the r-f output of the transmitter is connected between the wire conductor of the antenna and ground (fig. 129). Ground can be considered as one conductor of a transmission line and the antenna wire as the other conductor. As the r-f energy travels down the line, the distance traveled by the energy along the ground is less than the distance traveled by the energy along the wire, because of the lower velocity of propagation of the earth wave. This effect produces an out-of-phase relationship between the wire wave and the ground wave. As a result, the wave front is caused to tilt forward (fig. 129) and the traveling wave off the end of the antenna contains both vertical and horizontal components of wave energy with respect to a path of travel parallel to the ground. The radiated energy then is considered as elliptically polarized. At a distance from the transmitter, however, the predominant component of polarization is vertical, as a result of normal ground-wave propagation effects.

(1) Generally, the forward or desired radiation increases as the antenna is lengthened. As an example of the effect of difference in length on efficiency, data taken on 1,200-foot and 3,600-foot wave antennas at 250 kc and 500 kc erected over poor ground are indicated in the following chart:

Length (ft)	250 kc		500 kc	
	Length (wavelength)	Gain	Length (wavelength)	Gain
1,200	0. 306	0 db	0. 612	0 db
3,600	. 918	8 db	1. 826	9 db

Note. Gain of the 1,200-foot antenna is taken as 0 db at each frequency.

(2) Experimental data indicate that a wave antenna having a wire length equivalent to 2 wavelengths and erected over poor ground has a radiation efficiency in the forward direction equivalent to the radiation of a quarter-wave vertical antenna. A wave antenna having a wire length equivalent to 4 electrical wavelengths under the same conditions shows a radiation efficiency in the forward direction equivalent to a half-wave vertical antenna. Experiments in the range of 100 to 200 kc with wave antennas of 0.6 to 1.5 wavelengths, compared with standard-type flat-top antennas mounted on 180-foot towers, showed gains of approximately 10 db for the wave antenna. Highest gains were noted with the longer

wave antennas erected over poor ground.

(3) The efficiency of the wave antenna increases rapidly as the height is increased from 0 to the range of 12 to 15 feet. Above 15 feet, there is little increase in efficiency.

d. Receiving Antennas. Wave antennas also are used for receiving and, in this application, their performance also depends on wave tilt. However, when receiving, the radio waves approaching the antenna already are tilted because of their propagation over poor soil in the locality of the antenna.

(1) As the tilted wave moves in a direction from the terminating resistor toward the receiver, energy is induced along both the antenna wire and the ground. The effect of this induced energy is cumulative, since energy from the traveling wave is absorbed by the antenna, and a large current is produced at the input to the receiver. Actually, the induction of energy along the ground is a continuing process throughout the entire travel of the wave and not only at the antenna location. When so regarded, the antenna wire can be considered as the medium of extracting energy from the space surrounding it, and guiding this energy to the receiver with the proper phasing with respect to the receiver ground, so that a high level input is obtained.

(2) The polar pattern of the antenna is the same for transmitting and receiving, with maximum antenna gain in a direction from terminating resistor to receiver. When maximum gain is desired in the opposite direction, a special circuit arrangement can be used. This arrangement consists of using reflection transformers at each end of the antenna and placing the terminating resistor at the receiver location.

(3) When bidirectional reception is desired, the normal antenna circuit is used except for omission of the terminating resistor.

e. Feeding Methods.

(1) Since the wave antenna is a grounded antenna with a wide frequency range, it usually is fed by means of an unbalanced, nonresonant transmission line. The input impedance of the single-wire antenna is approximately 500 ohms, so that the characteristic impedance of the line also must be 500 ohms.

(2) The most common feeding arrangement is a single-wire transmission line connected to the end of the antenna. If coaxial line is to be used, an impedance-matching transformer is inserted between the transmission line and the antenna.

89. V Antenna

a. General Description. The V antenna consists of two horizontal, long wires arranged to form a V, and fed at the apex with currents of opposite polarity. Major lobes from each wire combine in such a way that maximum radiation occurs in the direction of a line that bisects the angle between the two wires. Figure 131 shows a V antenna with the individual radiation patterns of each of the wires. The shaded lobes produced by each individual leg of the V lie in exactly the same direction. These lobes combine to form the shaded lobes in the resultant pattern. Most of the other lobes are more or less attenuated. The pattern is bidirectional, and radiation occurs along a line that bisects the apex angle in both directions.

b. Design.

(1) As with other long-wire antennas, the greater the leg length the higher the gain and directivity of the antenna. The gain of the V antenna is about twice that of a single long-wire antenna, since the radiation from the lobes of two wires combines to produce the radiation pattern of the V antenna. In actual practice, the gain may be even higher than this value because of the effects of one leg of the V on the other.

(2) The following chart shows the approximate power gains of V antennas for various leg lengths, using the optimum value of apex angle in all cases.

Antenna length (wavelengths)	Power gain	Antenna length (wavelengths)	Power gain
1	2.1	6	8.0
2	2.9	8	11.9
3	3.8	10	17.8
4	5.0		

(3) The optimum apex angle for the V antenna is, ordinarily, twice the angle between the lobe of maximum radiation and the wire itself when the wire is used as a conventional long-wire antenna. Here, the lobes of maximum radiation from the two long wires making up the V antenna are in the same direction so that they combine as shown in figure 131. In practice, a somewhat smaller angle than this value is used when the V-antenna legs are shorter than about 3 wavelengths. This increases slightly the gain of the antenna.

(4) The following chart shows the optimum apex angle for V antennas with equal legs of various lengths:

Antenna length (wavelengths)	Optimum apex angle (degrees)	Antenna length (wavelengths)	Optimum apex angle (degrees)
1	90	6	40
2	70	8	35
3	58	10	33
4	50		

(5) When the V antenna is to be operated over a wide frequency range, an average optimum apex angle should be used. Reasonably good results are obtained by noting the optimum apex angle for the antenna at its lowest operating frequency and the angle for its highest operating frequency, and then using the average of these two values.

(6) The V antenna does not radiate the major portion of its energy along the surface of the earth. Instead, the energy is radiated upward at a certain vertical angle in respect to the earth. The size of this angle depends on the length of the antenna legs and the height of the antenna above ground. In general, as the antenna length is increased or as the height above ground is increased, the vertical angle at which maximum radiation occurs gradually becomes smaller. The vertical angle is measured in respect to the horizontal antenna wires.

(7) The following chart gives the approximate value of the vertical angle at which maximum radiation occurs for V antennas of various lengths. A height above ground of a half-wavelength is assumed.

Antenna length (wavelengths)	Vertical angle (degrees)	Antenna length (wavelengths)	Verticle angle (degrees)
1	31	6	16
2	27	8	14
3	23	10	13
4	20		

c. Feeding Methods. Balanced lines are used to feed the V antenna. Resonant lines are used if a wide frequency range is to be covered. Nonresonant feeders can be used in conjunction with quarter-wave matching sections at the apex of the V antenna, but only a fairly narrow frequency band can be accommodated.

d. Unidirectional V Antenna.

(1) The V antenna can be made unidirectional by making the antenna nonresonant. This is accomplished by connecting noninductive resistors of about 500 ohms between the far end of each leg of the V antenna and ground (*A* of fig. 132). The resistors must be able to dissipate about one-third the power applied to the antenna and must go to a good ground. Since no standing waves exist on the antenna, the length of the legs need not be a multiple of the half-wave. In a nonresonant antenna, maximum radiation occurs in the direction of the terminating resistor. The lobe of maximum radiation then is directed toward the open mouth of the V antenna, whereas the radiation in the opposite direction is largely suppressed.

(2) A unidirectional V antenna is shown in figure 132. The exact values for the terminating resistors can be found by a cut-and-try method in which various values of resistance are used until minimum standing waves appear on the antenna. The proper value should be in the vicinity of 500 ohms. A nonresonant open-wire line is used to feed the antenna. The unidirectional radiation pattern produced by this antenna is shown in *B* of figure 132.

e. Obtuse-Angle V Antenna.

(1) If the angle between the legs of the V antenna is greater than 90°, the antenna

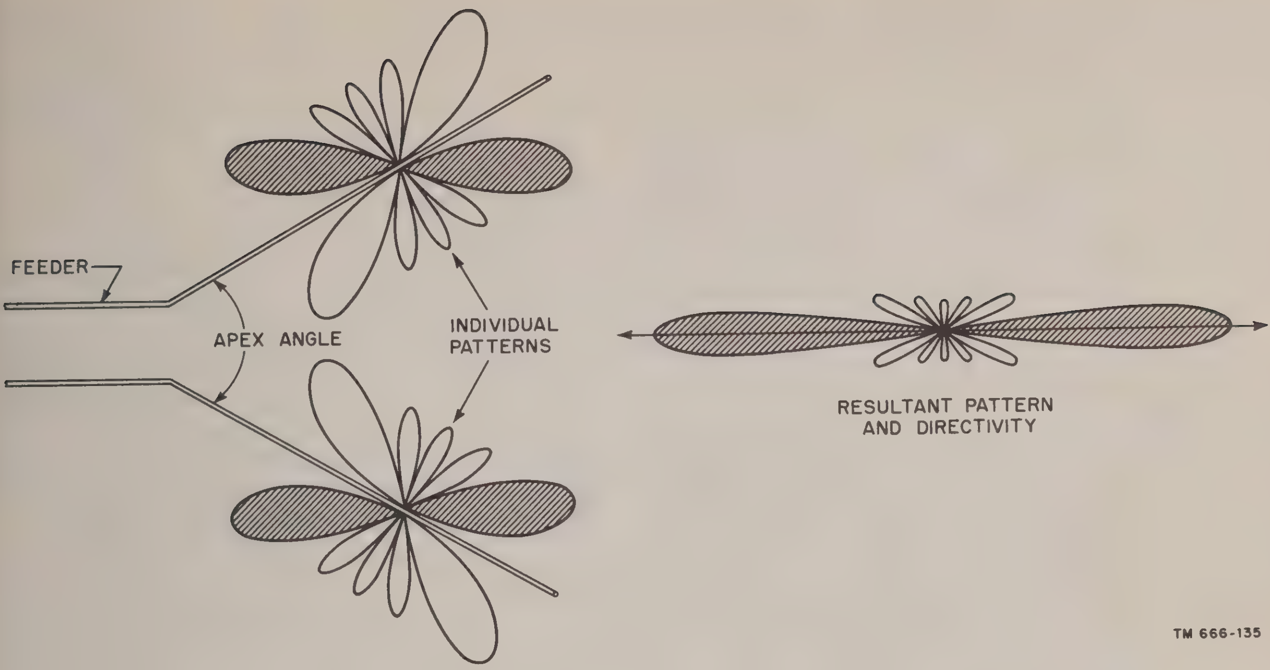

Figure 131. Formation of radiation pattern of V antenna.

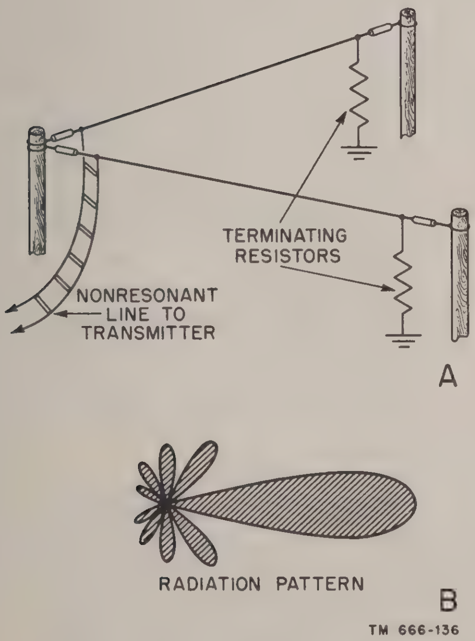

Figure 132. Unidirectional V antenna.

is an obtuse-angle V antenna (fig. 133). The value of the obtuse angle is obtained by subtracting from 180° the value of apex angle for the conventional V antenna with the same leg length.

(2) The following chart shows the correct angle for obtuse-angle V antennas of various leg lengths:

Antenna length (wavelengths)	Angle between legs (degrees)	Antenna length (wavelengths)	Angle between legs (degrees)
1	90	6	140
2	110	8	145
3	122	10	147
4	130		

(3) The obtuse-angle V antenna has the advantage of maintaining the same directivity over a wide frequency range. This is so because when the frequency is changed, the major lobe of radiation produced by one leg shifts in one direction and the major lobe produced by the other leg shifts in the opposite direction. Al-

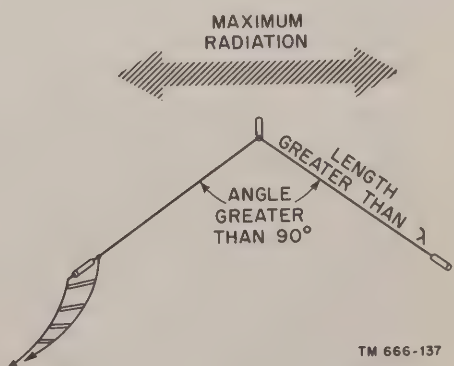

Figure 133. Obtuse-angle V antenna.

though a broadened lobe occurs and the gain is reduced somewhat, the directivity is exactly the same. Obtuse-angle V antennas frequently are terminated by a resistor, however, which makes the antenna nonresonant and unidirectional. Such obtuse-angle V antennas are known as half-rhombic antennas.

(4) The obtuse-angle V is objectionable because it requires twice the distance of an ordinary V antenna and produces less gain. For this reason, this antenna is not too popular.

f. Combination V Antennas.

(1) A single unterminated V antenna radiates energy in two directions that are opposite to each other. Combinations of V antennas can be used if it is desired to cover more directions. For example, nine 6-wavelength antenna wires can be erected radially with angles of 40° between them like the spokes in a wheel. This forms nine V antennas, with all apexes meeting at a common point. Each one of the radial wires serves as a leg for two adjacent V antennas. Separate feeder lines are used for each V antenna. Any one of nine different directions can be covered by selecting the proper feeder lines.

(2) The radiated power produced by a V antenna can be doubled approximately by the use of two V antennas operating simultaneously. There are, in general, three methods of arranging these two antennas. First, they can be erected parallel to each other in such a manner that one of the V's is a half-wavelength above the other. They now are said to be stacked. When the antennas are fed in phase, approximately twice the radiated power is produced. The vertical angle of maximum radiation is reduced. Second, the antennas can be erected in such a way that a W is formed. The two V's making up the W must be fed in phase. Third, the two antennas may be at the same height above ground, but one V is located a quarter-wavelength in front of the other. When the antennas are fed so that their currents are 90° out of phase, unidirectional radiation occurs. The maximum radiation is in the direction of the antenna with the lagging current. These are called V *beams*. The same principles apply to combinations of V antennas to produce beams as apply to combinations of other antennas for the same purpose (pars. 94 through 109).

90. Half-rhombic Antenna

a. General Description. The half-rhombic antenna is a terminated vertical antenna which resembles the obtuse-angle V antenna. With the obtuse-angle V, a balanced transmission line is used and ground does not form part of the radiating system. With the half-rhombic antenna, however, an unbalanced transmission line is used and ground or a counterpoise is utilized. As a result, a vertically polarized radio wave is produced.

b. Directional Characteristics.

(1) The development of the radiation pattern produced by the half-rhombic antenna is shown in figure 134. In *A*, the half-rhombic antenna has not been terminated. Assume that each leg is 2 wavelengths and that the angle between the two legs is correct. A transmitter is connected between the end of the antenna and a good ground. A single-wire counterpoise frequently is used which extends for the entire projection of the antenna length on the ground. Current from the transmitter flows toward the unterminated end of the antenna where it is reflected back along the antenna, as shown by the arrows. As a result of this reflection, standing waves are set up on the antenna and lobes of radiation appear as shown.

(2) Lobe 2 combines with lobe 5 to produce strong forward radiation from left to right. Lobe 4 combines with lobe 7 to produce strong rear radiation from right to left. These lobes exhibit bidirectional directivity along the direction of the antenna itself. The remaining lobes combine in various ways to produce several minor lobes in other directions. As a transmitting antenna, maximum energy is radiated in the directions shown by the large two-headed arrow, and as a receiving antenna best reception occurs in these same directions.

(3) When a terminating resistor of about 500 ohms is connected between the far end of

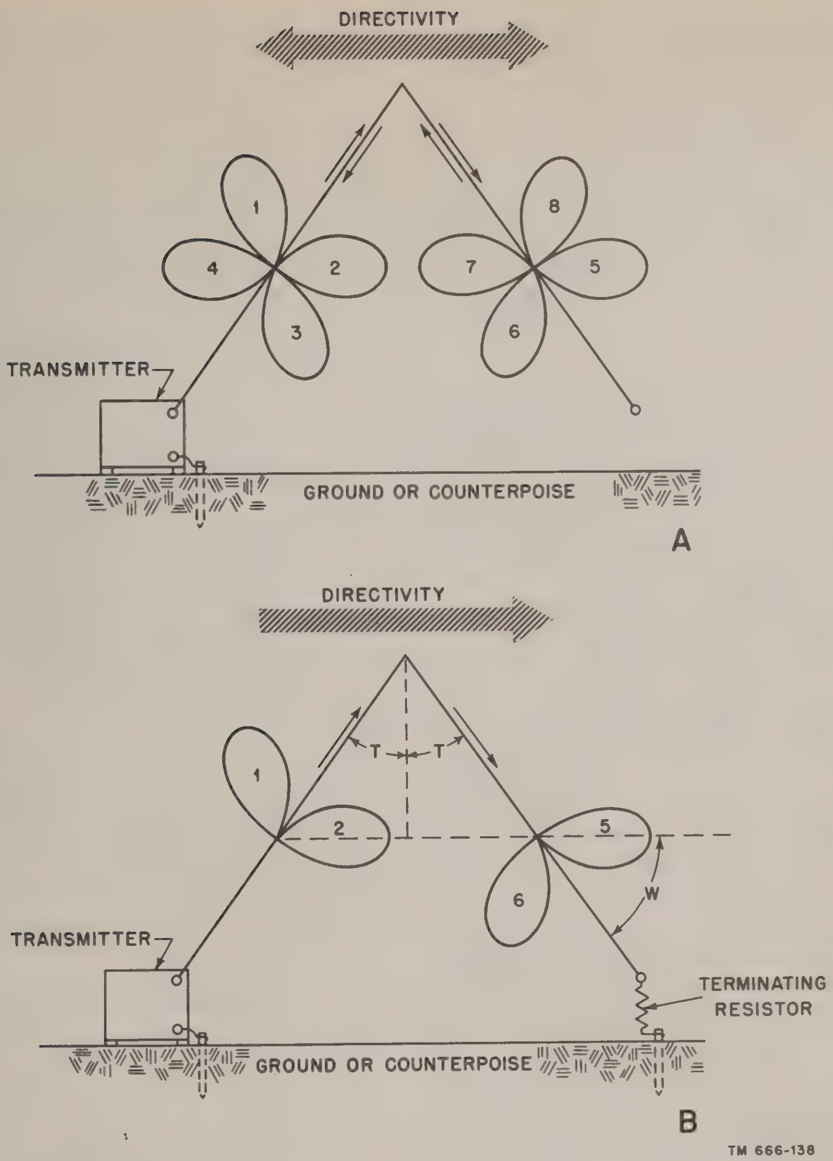

Figure 134. Development of radiation pattern of half-rhombic antenna.

the antenna and ground (or counterpoise), conditions become different. Current from the transmitter can flow only toward the resistor, as shown in *B*. This resistor absorbs any energy that is not radiated, and, in so doing, prevents any reflection of energy back along the antenna. As a result of using the terminating resistor, lobes 3, 4, 7, and 8 disappear and only the forward lobes remain. Lobes 2 and 5 combine to produce intense radiation in the forward direction, from left to right, whereas lobes 1 and 6 produce minor lobes. Consequently, when this half-rhombic antenna is used for transmission, it is unidirectional, and radiates maximum energy along the antenna in the direction of the terminating resistor, as shown by the large arrow in *B*.

(4) When the antenna is used for receiving, the antenna current will flow from the terminating resistor toward the receiver. Signals originating from the direction of the resistor will produce maximum effect on the receiver. Under these conditions, all arrows in *B* would be shown reversed. This is in accordance with the usual reciprocity of antennas.

(5) Two important angles are illustrated.

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T, commonly known as the *tilt angle,* is half the apex angle between the two legs of the antenna. It is made to have a certain value which is determined by the leg length. The *wave angle,* W, is between either maximum lobe of radiation and the antenna wire itself. The same value for this angle is obtained if measurement is made between lobe 5 and its antenna leg or between lobe 2 and its antenna leg.

c. *Design Information.*

(1) Assume that a unidirectional half-rhombic antenna using a single-wire counterpoise is to be designed. It is desirable that the legs of the antenna be many wavelengths in order to provide maximum gain and directivity. For satisfactory performance, each leg of a half-rhombic antenna must be at least 1 wavelength at the lowest frequency of operation. In practice, a leg of at least 2 wavelengths at the lowest frequency generally is used, and some half-rhombic antennas use legs of 10 or 12 wavelengths. The leg length usually is limited by the size of the available site and the directivity required.

(2) The half-rhombic antenna maintains its characteristics over a wide frequency range. Frequency ranges of 2 to 1 and 4 to 1 are common in practice. For example, a half-rhombic antenna dedigned for a frequency of 10 mc would operate satisfactorily to 20 mc and would be useful to 40 mc. Depending on the amount of change in gain and directivity that can be tolerated, an even greater frequency range can be accommodated. In general, as the frequency is raised, greater gain and directivity occur.

(3) Once the leg length has been decided, it is necessary to determine the tilt angle required for that leg length. The optimum value of tilt angle is a compromise between two sets of conditions. First, the tilt angle must have such a value that the lobes of maximum radiation from both legs are in exactly the same direction. This is necessary so that the two forward lobes can combine properly to produce the unidirectional pattern. This value of tilt angle is simply 90° less than the wave angle. Second, the tilt angle must have such a value that the radiation in the forward lobe of one leg of the half-rhombic antenna combines in phase with the radiation in the forward lobe of the other leg. This usually requires the projection of either leg of the half-rhombic antenna on the ground to be a half-wavelength shorter than the actual length of the leg. When this condition is met, the tilt angle will be somewhat smaller than the first value obtained. In practice, the actual size of the tilt angle is a compromise between these two values.

(4) The following chart gives the value of tilt angle to be used in half-rhombic antennas of various leg lengths. As in most of the charts given so far, antenna length is expressed in wavelengths. In order to convert these lengths to feet, the formula given previously can be used. The formula is:

$$\text{length (feet)} = \frac{492(H-0.05)}{\text{frequency (mc)}}$$

where H is the number of *half*-waves on the antenna. A somewhat more convenient form is:

$$\text{length (feet)} = \frac{984(N-0.025)}{\text{frequency (mc)}}$$

where N is the number of *full* waves on the antenna. Because the length is not especially critical and the end effect is so small for long antennas, the factor 0.025 may be neglected in practice. If the value of the angle between the two legs of the half-rhombic antenna is desired, simply double the value of the tilt angle.

Antenna length (wavelenghts)	Tilt angle (degrees)	Antenna length (wavelengths)	Tilt angle (degrees)
1	30	6	67
2	50	8	70
3	57	10	71
4	62	12	73

(5) Once the tilt angle and leg lengths are known, the height of the apex of the antenna above ground and the required counterpoise length can be calculated. In figure 135, a right triangle is formed by one of the legs of the antenna, L,

the height of the apex above ground, H, and one-half the length of the counterpoise, $\frac{1}{2}$ C. The tilt angle, T, is one of the angles in the right triangle. The ratio of the height to the leg length, H/L, is equal to the cosine of the tilt angle, cos T. Assuming that the leg is 2 wavelengths and the tilt angle is 50°, as shown in the preceding chart, the following relation can be written and solved:

$$\cos T=\frac{H}{L}$$

$$\cos 50°=\frac{H}{2}$$

$$0.643=\frac{H}{2}$$

$$H=1.286 \text{ or } 1.3.$$

Hence, the height of the apex is 1.3 wavelengths above ground. To convert this height into feet, it is necessary only to use the same formula ((4) above) for converting lengths in wavelengths to feet, except that end effect need not be considered. Simplified, the formula is:

$$\text{length (ft)}=\frac{984\ N}{\text{frequency (mc)}}$$

where N is the number of full wavelengths.

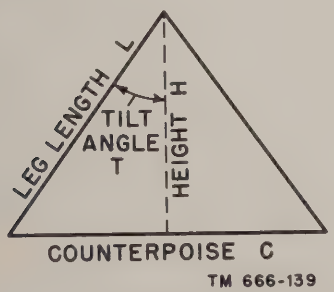

Figure 135. Right triangle formed by half-rhombic antenna.

(6) The ratio between one-half the length of of the counterpoise, $\frac{1}{2}$ C, and the leg length, L, is equal to the sine of the tilt angle, sin T,. Using this relation, the length of the counterpoise can be calculated for the example given above as follows:

$$\sin T=\frac{\frac{1}{2}C}{L}$$

$$\sin 50°=\frac{\frac{1}{2}C}{2}$$

$$0.766=\frac{\frac{1}{2}C}{2}$$

$$\tfrac{1}{2}C=1.532 \text{ or } 1.5$$

$$C=3.$$

Therefore, the counterpoise required is 3 wavelengths.

(7) The following chart gives the height of the apex and the length of the counterpoise required, both in terms of wavelengths at the operating frequency, for half-rhombic antennas of various leg lengths.

Leg length (wavelength)	Apex height (wavelengths)	Counterpoise length (wavelengths)
1	0. 87	1
2	1. 3	3
3	1. 6	5
4	1. 9	7
6	2. 3	11
8	2. 7	15
10	3. 3	19
12	3. 5	23

d. Practical Antennas.

(1) The factor that most frequently limits the size of the half-rhombic antenna is the height of the apex above ground. If a very tall support is available for the apex, a large antenna can be erected. It is necessary that the single support required be made of wood, or other nonconductor, so that the operation of the antenna is not affected. Steel masts, or wooden masts using metal guy wires, should not be used.

(2) The typical military half-rhombic antenna shown in figure 136 consists of a 100-foot antenna wire erected over a single 30-foot wooden mast (supported by three rope guys) and an 85-foot counterpoise wire laid along the ground. The antenna and counterpoise are terminated in a 500-ohm resistor contained

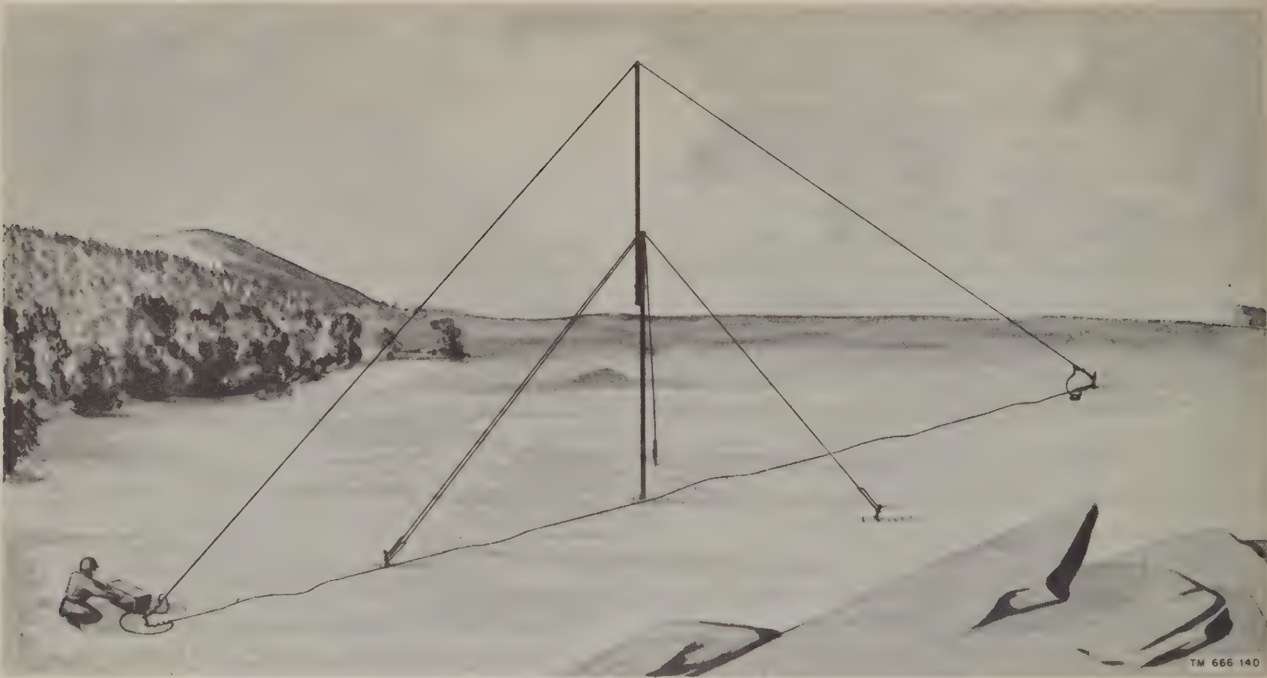

Figure 136. Typical military half-rhombic antenna.

in a small terminal box at the far end of the antenna.

(3) The antenna shown can be used with low-power transmitters or receivers operating at frequencies from 30 to 70 mc and equipped with either an r-f output impedance of 500 ohms or a suitable antenna-matching network. At 30 mc, the leg is 1½ wavelengths, and at 70 mc it is 3½ wavelengths. A power gain of 4 or 5 occurs at the lowest frequency, and a power gain of about 10 occurs at the highest operating frequency.

(4) Since the transmitter or receiver used with the half-rhombic antenna generally is located at the end of the antenna, direct connections can be made to the antenna. If a transmission line must be used between the antenna and the radio set, a two-wire line with a characteristic impedance of 500 ohms can be used.

(5) A large half-rhombic antenna, designed for frequencies from 3 to 18 mc, has a ground-projected length of 625 feet and an apex height of 225 feet. The antenna is supported by a hydrogen-filled balloon in low winds or by a kite in high winds. A ballon- or kite-supported half-rhombic antenna, designed for frequencies of 1 to 8 mc, has a ground-projected length of 1,600 feet and an apex height of 560 feet.

91. Rhombic Antenna

a. General Description.

(1) The highest development of the long-wire antenna is the rhombic antenna (fig. 137). It consists of four conductors joined to form a rhombus, or diamond. All sides of the antenna have the same length and the opposite corner angles are equal. The antenna can be considered as being made up of two V antennas placed end to end and terminated by a noninductive resistor to produce a unidirectional pattern. A rhombic antenna can be made of two obtuse-angle V antennas which are placed side by side, erected in a horizontal plane, and so terminated as to be made nonresonant and unidirectional.

(2) In common with previous nonresonant antennas, the rhombic antenna radiates best in the direction of the terminating resistor and receives best from the direction of the resistor. Maximum radiation does *not* occur in the same direction as the plane of the antenna, that is, hori-

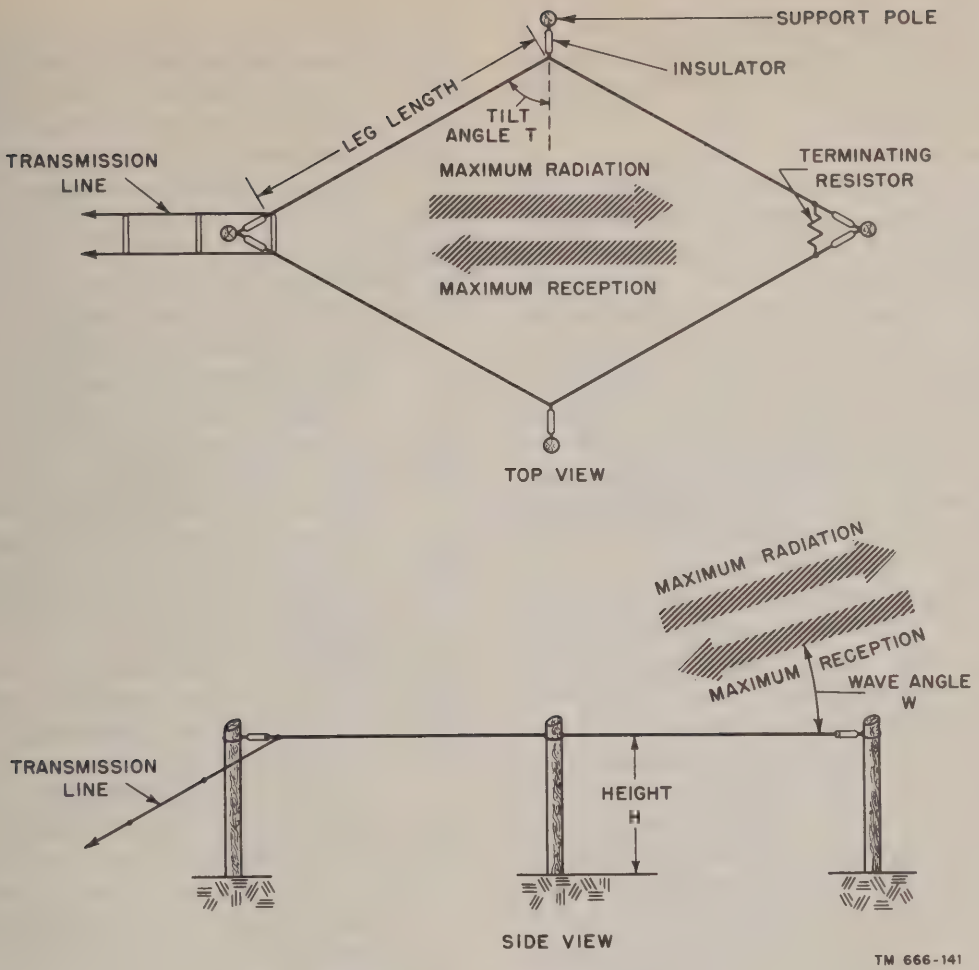

Figure 137. Basic rhombic antenna.

zontally. Instead, it occurs at some vertical angle above the horizontal plane, as shown by the wave angle, W. The tilt angle, T, is one-half the angle between the two legs making up one side of the antenna.

b. Advantages. The rhombic antenna is used widely for long-distance high-frequency transmission and reception, for reasons explained below. It is one of the most popular fixed-station antennas, being very useful in point-to-point work.

(1) The rhombic antenna is useful over a wide frequency range, a range of 2 to 1 being covered easily with excellent results. Although it is true that some changes in gain, directivity, and characteristic impedance do occur with change in operating frequency, these changes are small enough to be neglected. A frequency range of 4 to 1 can be covered by a typical rhombic antenna with good results, and standard military rhombics cover a frequency range of 5 to 1 or 6 to 1 satisfactorily.

(2) Another advantage of the rhombic antenna is that it is much easier to construct and maintain than other antennas of comparable gain and directivity. Only four supporting poles of common heights from 50 to 75 feet are needed for the antenna, which has a simple form, being made up of four straight lengths of wire.

(3) The rhombic antenna also has the advantage of being noncritical so far as operation and adjustment are concerned. This follows from the broad frequency characteristics of the antenna.

(4) Still another advantage is that the voltages present on the antenna are much lower than those that would be produced by the same input power on a resonant antenna. This is particularly important

when high transmitter powers are used or when high-altitude operation is required. The lower voltages mean less possibility of corona loss.

c. Disadvantages.

(1) The rhombic antenna is not without its disadvantages, probably the principal one being that a fairly large antenna site is required for its erection. Each leg is made at least 1 or 2 wavelengths at the lowest operating frequency, and when increased gain and directivity are required, legs of from 8 to 12 wavelengths are used. Such requirements mean that high-frequency rhombic antennas have leg lengths of several hundred feet, and they are used then only when a large plot of land is available.

(2) Another disadvantage is that the horizontal and vertical patterns depend on each other. If a rhombic antenna is made to have a narrow horizontal beam, the beam is also lower in the vertical direction. Therefore, it is impossible to obtain high vertical-angle radiation except with a very broad horizontal pattern and low gain. Rhombic antennas are used, however, for long-distance sky-wave coverage at the high frequencies. Under these conditions, low vertical angles of radiation (less than 20°) are desirable. With the rhombic antenna, a considerable amount of the input power is dissipated uselessly in the terminating resistor. However, this resistor is required in order to make the antenna unidirectional, and the great gain of the antenna more than makes up for this loss.

d. Operation.

(1) Figure 138 shows the individual radiation patterns produced by the four legs of the rhombic antenna and the resultant radiation pattern. If the tilt angle, *T*, is properly chosen for the length of the legs used, the shaded lobes all add together to form an intense forward lobe in the direction of the terminating resistor. The principle of operation is the same as for the V and the half-rhombic antennas.

(2) Practically all rhombic antennas are erected in the horizontal plane. The two sides of the antenna are fed with currents of opposite polarity. As a result, the vertical electric field component of the radiated energy produced by one side of the antenna is largely cancelled by an equal and opposite electric field produced by the other side of the antenna. Lines of electric force are produced from one side of the antenna to the other. Therefore, the polarization of the

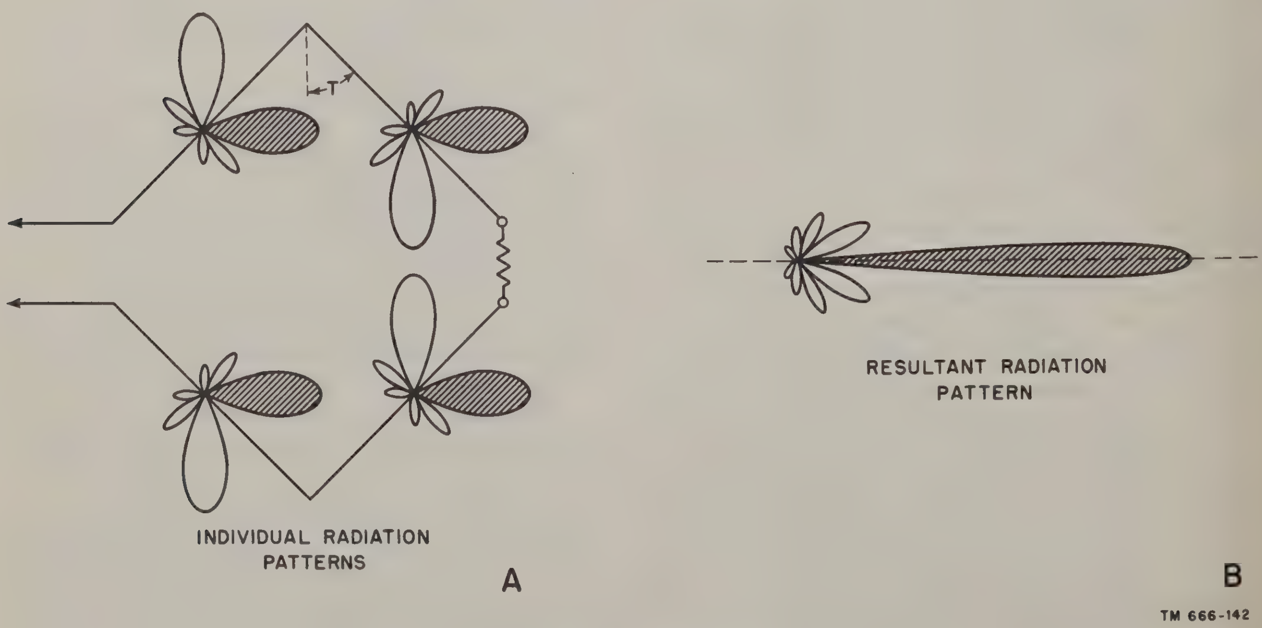

Figure 138. Formation of rhombic antenna beam.

radiated field produced by a horizontal rhombic antenna is mainly *horizontal*.

(3) Very small rhombic antennas can be used at the very-high or ultrahigh frequencies. These antennas are erected in a vertical plane and a vertically polarized wave is radiated. Since the greatest percentage of rhombic antennas are used at high frequencies where the lengths of the legs are several hundred feet, most rhombics are horizontal. Therefore, the horizontal polarization is most common.

e. Directivity and Gain.

(1) Typical radiation patterns produced by rhombic antennas having various leg lengths are shown in figure 139. These radiation patterns clearly show an increase in gain and a reduction in the beam width of the main lobe as the lengths of the legs are increased. The wave angle, *W*, also is reduced as the leg lengths are increased. Information concerning the exact dimensions for optimum output from a rhombic antenna is given in paragraph 91*i* (4).

(2) The gain of the rhombic antenna for a given leg length is considerably greater than for any of the other long-wire antennas discussed previously. The approximate power gains of rhombic antennas of various leg lengths are shown in the following chart, which takes into account the power lost in the terminating resistor.

Leg length (wavelengths)	Power gain	Leg length (wavelengths)	Power gain
1	2. 5	6	17. 0
2	5. 4	8	22. 4
3	8. 3	10	28. 2
4	11. 2		

f. Terminating Devices.

(1) To operate properly, the rhombic antenna must be terminated correctly by correct value of resistance, which will make it unidirectional and nonresonant. The input impedance of the rhombic antenna then remains constant over a wide frequency range, and antenna coupling circuits need not be readjusted when the frequency applied to the antenna is changed. The proper value for the termination is about 800 ohms. When this is used at the far end of the antenna, the input impedance of the antenna is approximately 700 to 800 ohms. Thus, the terminating resistor is slightly higher in value than the input impedance of the antenna, because of the loss of energy by radiation as the traveling wave from the transmitter moves toward the terminating resistor.

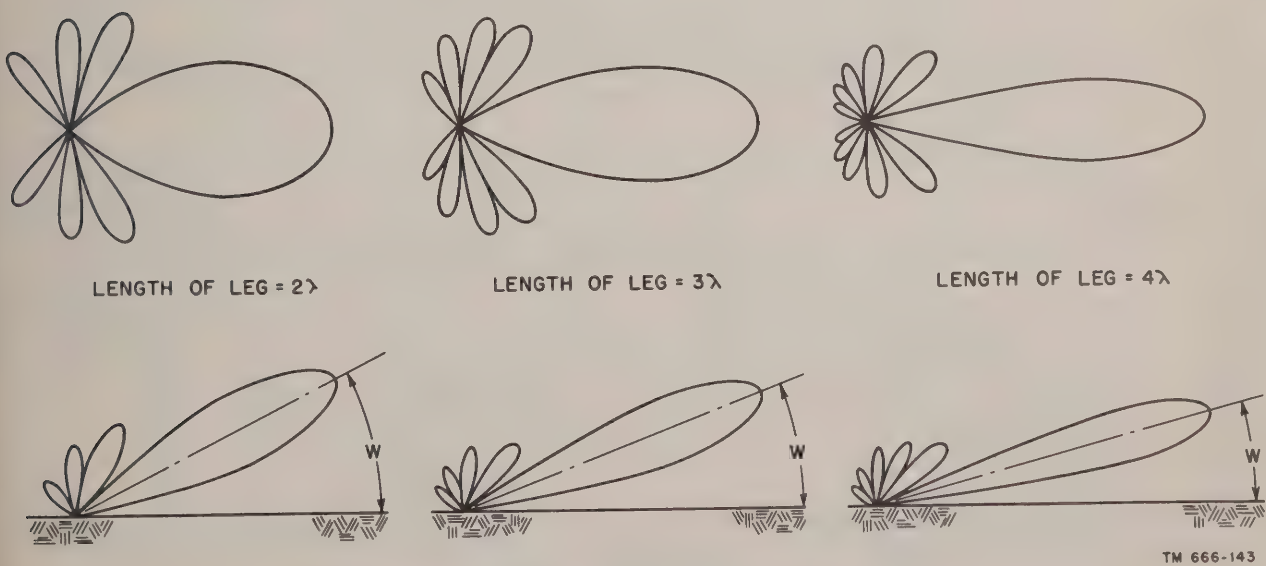

Figure 139. Radiation patterns produced by various rhombic antennas.

(2) The termination used with the rhombic antenna must be a pure resistance at all frequencies at which the antenna is to operate. If any reactance is associated with the termination, some reflection of energy occurs and standing waves are set up on the antenna, causing variations in characteristics and radiation pattern when the frequency applied to the antenna is changed.

(3) The terminating resistance must dissipate a little less than one-half the power applied to the input terminals of the antenna. For transmitter powers up to 1,000 watts, noninductive carbon resistors generally are used. These resistors are available in power ratings up to approximately 100 or 200 watts each. Frequently, several resistors are paralled to provide for adequate power rating. The total rated wattage of the resistors should equal one-half the transmitter wattage. For example, five 150-watt, 3,000-ohm carbon resistors connected in parallel provide a 600-ohm load (required for special types of rhombics) which will handle a transmitter power of 1,000 watts with a 50-percent safety factor. To reduce capacitance in the terminating load, several resistors sometimes are connected in series, and the capacitances across each resistor then are in series so that a reduction in termination capacitance results. The terminating resistors frequently are mounted within a weatherproofed wooden box located atop the pole which supports the terminated end of the antenna. Connecting leads to the terminating resistors are made as short as possible to minimize the amount of added reactance.

(4) The insulators used with the rhombic antenna, and the supporting wires and fittings, sometimes introduce enough reactance to require precise adjustment of the terminating load to balance it out. It is more convenient, then, to mount the terminating resistors in a box that is near the ground rather than at the top of a pole. When this is done, the far end of the rhombic antenna is connected to the terminating resistors by means of an 800-ohm nonresonant transmission line.

(5) For powers in excess of 1,000 watts, carbon resistors are not available that will dissipate the necessary power. Lengths of transmission line constructed to have the proper impedance value, and made of wire that is a poor conductor, are used.

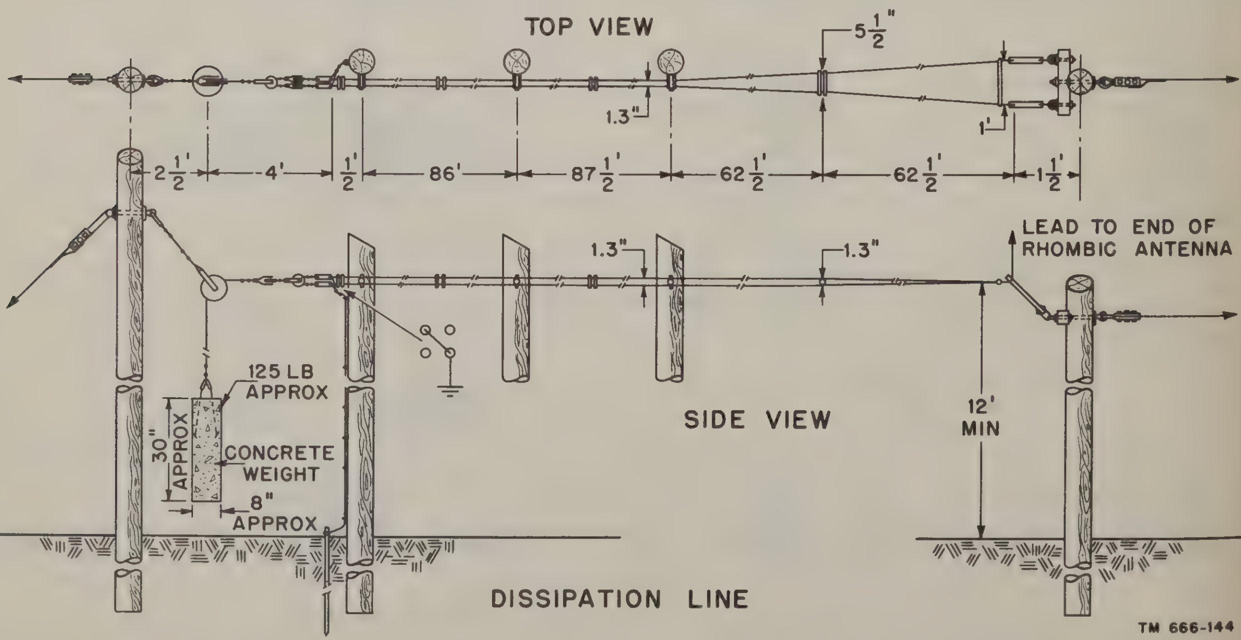

Figure 140. Dissipation line used with standard military rhombic antenna.

Most of these *dissipation lines* are made of #14 AWG solid, annealed, stainless-steel wire, and take two general forms:

(*a*) One, a two-wire stainless-steel transmission line, is spaced properly to provide a correct termination for the rhombic antenna. The spacing is uniform along the entire length of the line. If sufficient length is provided, the energy is so attenuated by the high resistance of the wire that the far end can be grounded directly for lightning protection. One such dissipation line is 1,000 feet long and is run back and fourth four times between supporting poles, 250 feet apart. The entire dissipation line is mounted beneath the rhombic antenna which it terminates.

(*b*) A more common dissipation line which requires less than one-third as much steel wire is shown in figure 140. This line is used with standard military rhombic antennas.

(6) The dissipation line includes, all in one length, the downlead from the end of the rhombic antenna. The downlead portion is made up as a two-wire line with each wire being made of two strands of the steel wire twisted together. The spacing between the two wires is 12 inches so that the characteristic impedance produced is about 650 ohms. The downlead becomes part of the horizontal portion of the dissipation line by a right-angle bend, and at this point a modified exponential line begins (fig. 141).

(7) The two-wire downlead is transformed into a four-wire dissipation line without the necessity of joining or splicing. The 12-inch spacing starts diminishing and the two strands making up each line of the two-wire line now become separate spaced lines. In this manner, in a line length of 62.5 feet, the 12-inch spacing tapers down to a 5.5-inch spacing as the side members spread apart to 1.3 inches at the dissipation-line spreader insulator. From this point on, in a line length of an additional 62.5 feet, the 5.5-inch spacing tapers down to 1.3 inches, whereas the

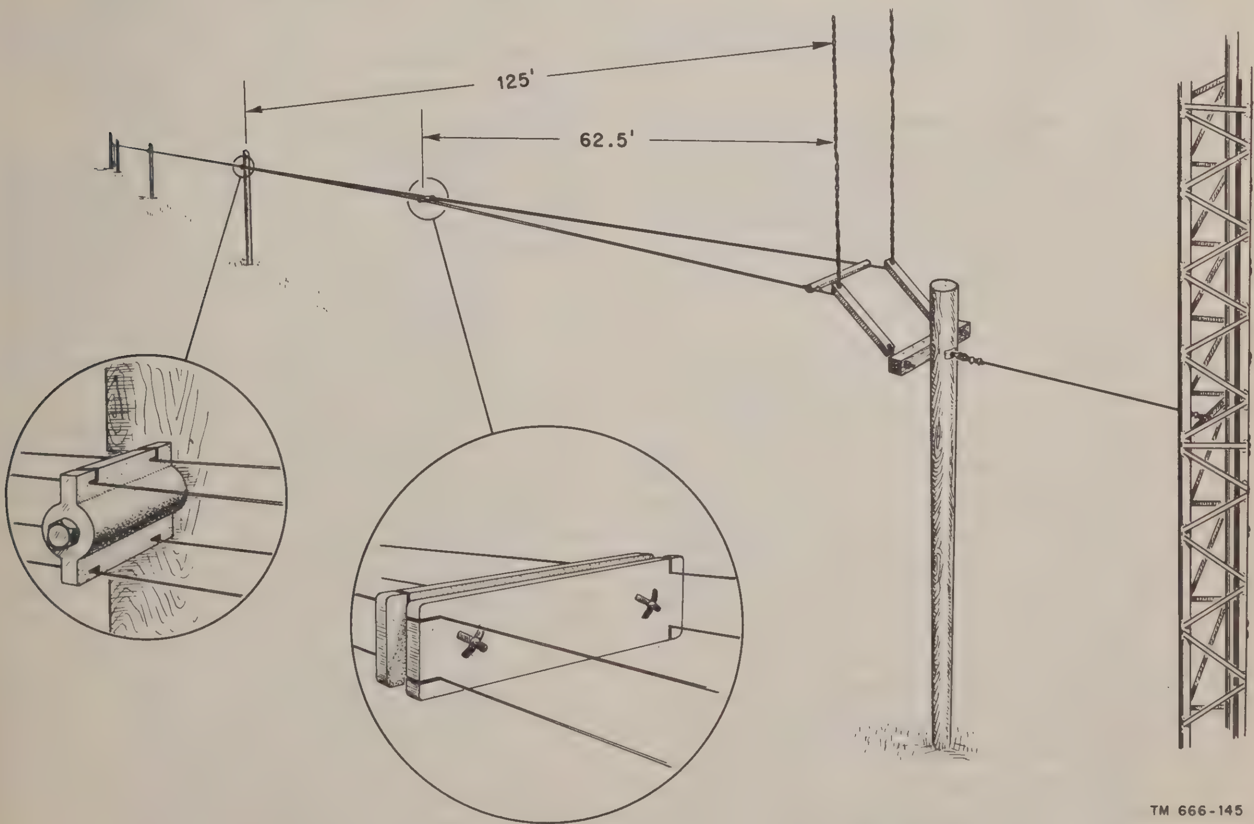

Figure 141. Dissipation line detail showing terminating assembly.

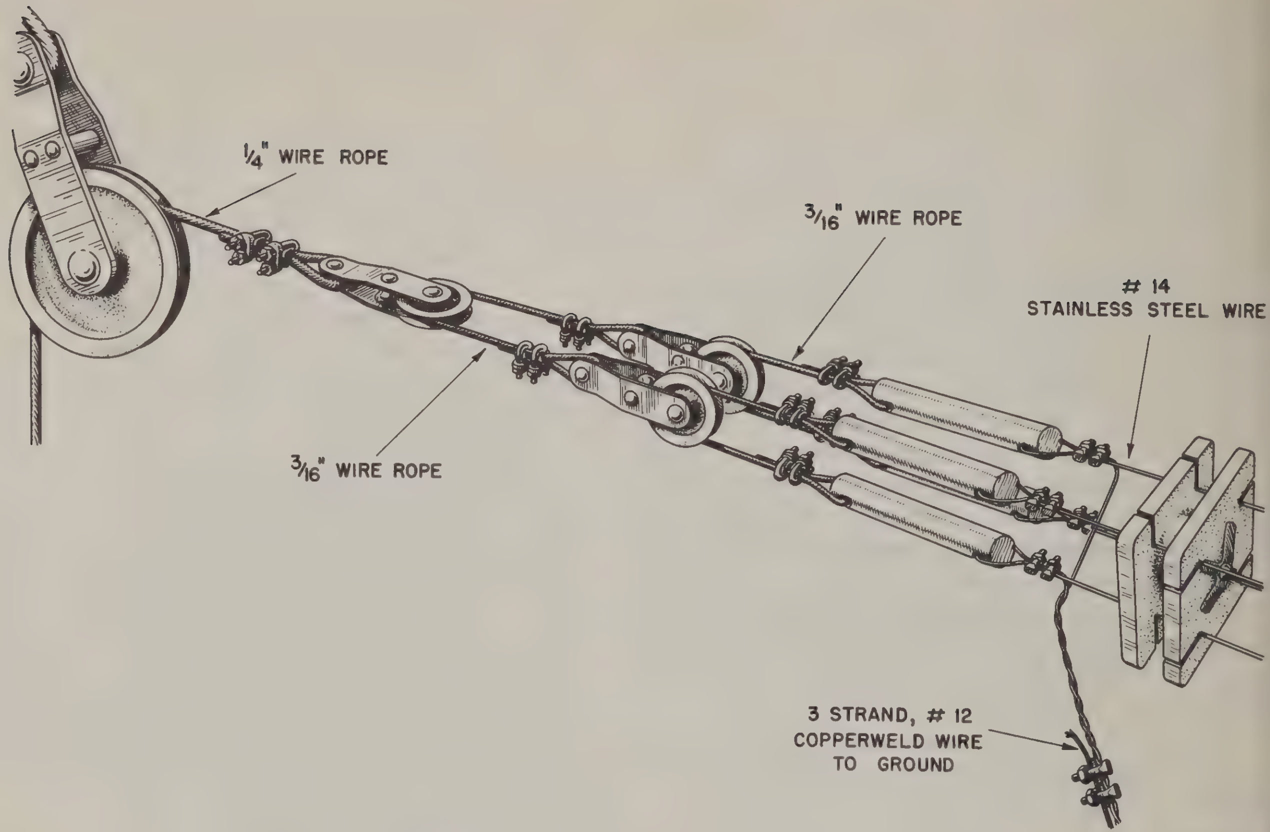

Figure 142. Dissipation line detail showing terminating assembly.

side members remain spaced 1.3 inches apart. Then, the line continues as a 1.3-inch, square-spaced, four-wire line. The modified exponential portion of the dissipation line transforms the approximately 650-ohm impedance of the downlead to about 200 ohms.

(8) The equally spaced four-wire portion of the dissipation line is fundamentally two 400-ohm lines in parallel, one terminated in an open circuit and the other terminated in a short circuit. Such an arrangement improves the electrical balance and symmetry of the termination. The short-circuited end can be connected to ground (fig. 142) to provide for lightning protection. The three small pulleys shown are used to equalize the tension on the individual wires making up the line. A wire rope at the end of the assembly is passed through the large pulley and made fast to a concrete weight which maintains tension on the line, preventing excessive sagging.

g. Checking Termination.

(1) Unless the correct value of termination for the rhombic antenna is used, undesired resonance effects occur. This makes the antenna coupling critical, and adjustments must be made when the applied frequency is changed. Lack of symmetry from improper termination causes an undesirable shift in the directivity pattern of the antenna, and the resultant unbalanced reactance may introduce undesirable resonance effects.

(2) In checking the rhombic antenna for proper termination, advantage is taken of the fact that a properly terminated antenna has an input impedance that is purely resistive. With a perfectly balanced antenna having the correct value of terminating resistance, no reflection of energy occurs on the antenna and no reactance appears at the input terminals. Therefore, if a balanced oscillator is connected to the input terminals of a properly terminated rhombic antenna, no

change in oscillator frequency should occur.

(3) The balanced (push-pull) oscillator used should have a high L-C ratio-tank circuit so that small values of reactance, which are usually capacitive with improperly terminated rhombic antennas, may have considerable effect on the oscillator frequency. To insure that the oscillator is not too heavily loaded, the correct tap points on the oscillator tank coil can be predetermined with an 800-ohm noninductive resistor as load.

(4) The oscillator first is set at a frequency within the operating range of the rhombic antenna. The oscillator frequency then is carefully measured with a heterodyne frequency meter or with a stable communication receiver having a beat-frequency oscillator, and the antenna is connected to the oscillator. If the rhombic antenna is perfectly terminated, the frequency meter or the receiver should indicate no change in oscillator frequency. In actual practice, since a perfect termination is difficult to produce, a very small frequency shift can be tolerated. A possibility exists in which little or no change in oscillator frequency occurs, with the antenna *not* properly terminated. This happens if the antenna is resonant at the particular frequency used for the check. To eliminate this possibility, the frequency shift should be measured at a different oscillator frequency. If considerable frequency shift occurs when the antenna is connected to the oscillator, a recheck should be done with the value of the terminating resistor changed about 5 or 10 percent, and this procedure should be continued until a resistance value is found that produces the least effect on the oscillator frequency when the antenna is connected. When a rhombic antenna is to be used over a wide frequency range, this procedure should be repeated for several frequencies within the desired frequency range. Then an average value for the proper terminating resistance can be used.

(5) To use the procedure explained above, it is necessary that the test oscillator be battery-operated and portable, so that the oscillator can be carried up the pole which supports the input end of the antenna to permit direct connections at the input terminals. If the oscillator must be used on the ground below the rhombic antenna, a length of two-wire line is used to connect it to the input terminals of the antenna. This line must be a half-wavelength at the frequency at which the rhombic termination is to be checked. The frequency of the oscillator should be adjusted so that there is no change in oscillator frequency when the connecting line is connected or disconnected from the oscillator. Several separate half-wave connecting lines must be used to check the antenna termination at several frequencies within the operating range.

h. Design Information.

(1) In designing a rhombic antenna, the first consideration is usually a determination of the wave angle, W, needed to cover the required distance when a given frequency is used at a certain time of the day. Such information can be obtained from charts and information given in TM 11–499, Radio Propagation Handbook.

(2) The following chart shows some typical wave angles required to provide sky-wave communication over various great-circle distances. The wave angles used are invariably less than 30°.

Great-circle distance (miles)	Wave angle (degrees)		
	1-hop E transmission	1-hop F transmission	2-hop F transmission
250	25		
500	13		
750	7	24	
1,000	4	17	
1,500		9	25
2,000		4	17
2,500			12

(3) For a given vertical wave angle, a rhombic antenna produces maximum power output when its leg length, L, tilt angle, T, and height above ground, H, have certain definite values. These values are all interdependent and any change

from the optimum value results in a reduction in power at the desired wave angle.

(4) The following chart gives the proper values for these factors at various wave angles. Wave angles less than 10° are not shown. This does not mean that such angles are not required but rather that the rhombic antenna designed for maximum output at such low angles is prohibitively large.

Wave angle (degrees)	Optimum tilt angle (degrees)	Optimum leg length (wavelengths)	Optimum height above ground (wavelengths)
10	80	17. 0	1. 45
14	76	8. 5	1. 04
18	72	5. 3	. 81
22	68	3. 7	. 67
26	64	2. 7	. 57
30	60	2. 0	. 50

(5) Frequently, a sufficiently large antenna site is not available for the erection of a rhombic antenna of proper size to produce maximum output. For example, according to the chart above, a leg of 17 wavelengths is required for a wave angle of 10°. If such an antenna is to operate on a frequency of 8 .mc, for example, each leg would have to be over 2,000 feet long. This antenna would require over a mile and a half of antenna wire for its construction, and the installation would prove difficult. Therefore, rhombic antenna dimensions are chosen which represent a compromise design.

(6) When a rhombic antenna is designed with leg length definitely limited, the gain of the antenna is less than if the dimensions shown in the preceding chart are used. All of the advantages of the antenna given previously still apply, however, and rhombic antennas of a compromise design are used widely.

(7) The following chart shows the dimensions to be used when constructing a rhombic antenna limited to legs of *2 wavelengths*.

Wave angle (degrees)	Tilt angle (degrees)	Height above ground (wavelengths)
5	52	3. 00
10	52. 5	1. 45
15	54	1. 00
20	55	. 75
25	57. 5	. 60
30	60	. 50

(8) When the limit is 3 wavelengths, the dimensions in the following chart apply. The required heights above ground are the same as given in the previous table for similar wave angles.

Wave angle (degrees)	Tilt angle (degrees)	Wave angle (degrees)	Tilt angle (degrees)
5	59	20	63. 5
10	60	25	65
15	62	30	----------

A tilt angle is not given when a wave angle of 30° is required. No compromise in design is needed, since a rhombic antenna with leg limited to only 2 wavelengths and with a tilt angle of 60° can be used to produce maximum output.

(9) When the leg is limited to *4 wavelengths*, the dimensions given in the following chart apply. Here again the required heights above ground are the same as those given in the previous charts for similar wave angles. Where no tilt angle is given, no compromise in dimensions is required.

Wave angle (degrees)	Tilt angle (degrees)	Wave angle (degrees)	Tilt angle (degrees)
5	63. 5	20	68. 5
10	64. 5	25	----------
15	66. 5	30	----------

i. Standard Designs.

(1) Most rhombic antennas used for military applications are based on certain standardized dimensions which make satisfactory operation possible over a frequency range of from 4 to 22 mc. This range includes the frequencies that commonly are used for long-distance point-to-point

sky-wave communication between fixed stations.

(2) The seven standard sizes used are designated as rhombic antennas *A* through *G*, inclusive. Antenna *A* is the largest rhombic and it is used when communication is required between points over 3,000 miles apart. The leg of this antenna is about 1½ wavelengths at the lowest operating frequency (4 mc) and about 8½ wavelengths at the highest operating frequency (22 mc). Antenna *G*, the smallest rhombic, is used when communication is required between points that are from 200 to 400 miles apart. The leg of this antenna is somewhat less than 1 wavelength at the lowest operating frequency and about 5 wavelengths at the highest operating frequency. Rhombic antennas *B* through *F* inclusive have intermediate ranges and leg lengths.

(3) Complete kits are available which include all necessary material for the construction of standard military rhombic antennas. The four large poles or metal supports used are designated as side poles, front pole, and rear pole in the isometric view of the rhombic antenna (fig. 143). Terminating resistors, or a dissipation line, are connected at the corner of the antenna supported by the front pole. The transmission line which connects the transmitter or receiver to the antenna is attached to the corner supported by the rear pole. As shown in the plan view, the side poles and the front pole are located 3 feet from the corners of the antenna which they support, and the

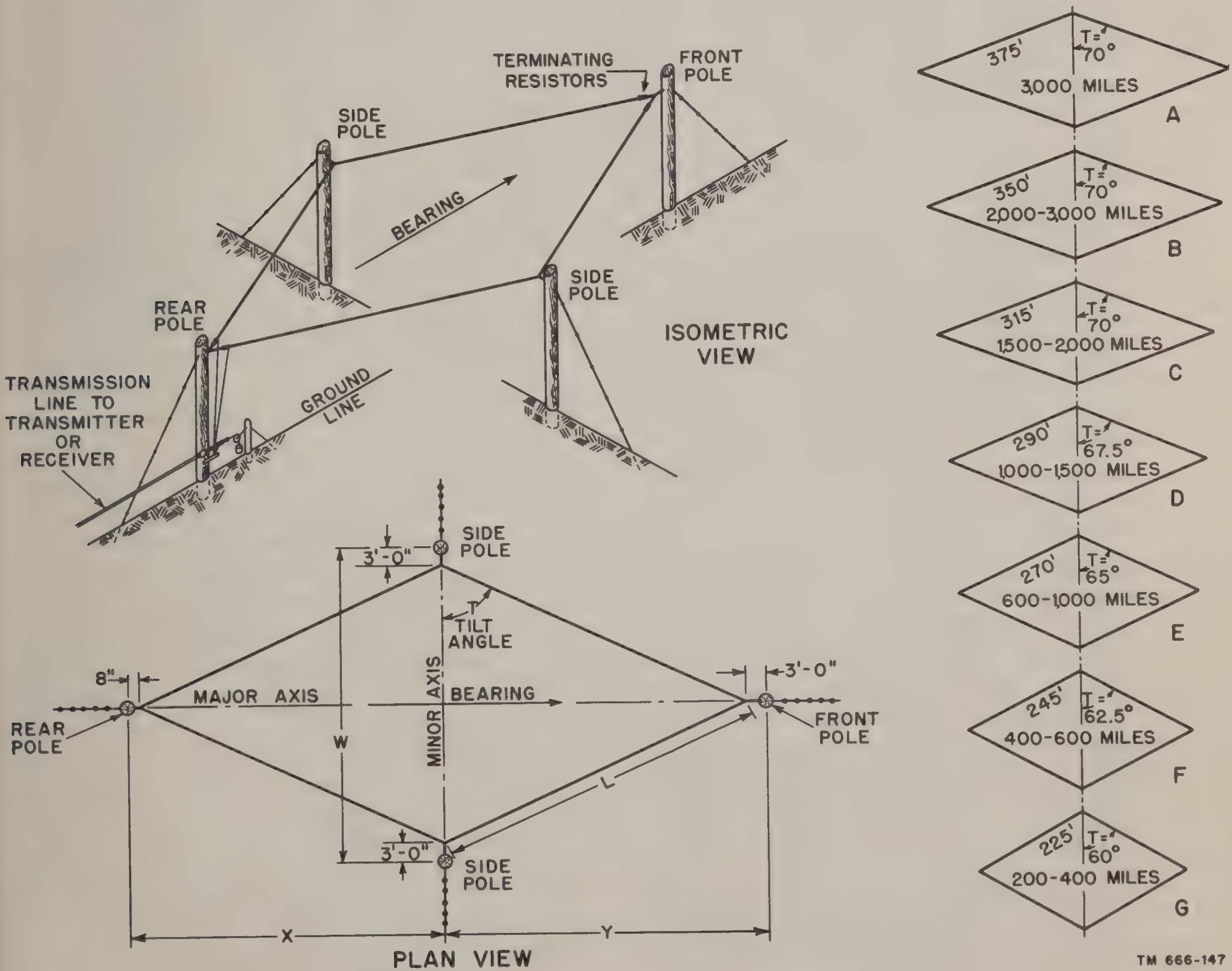

Figure 143. Standard military rhombic antennas.

rear pole is located 8 inches from the corner which it supports. These distances permit the installation of strain insulators and supporting harnesses which attach the antenna to the poles.

(4) The chart given below indicates the essential dimensions used in the seven standard rhombic antennas, along with the useful ranges of these antennas. The various letters designate dimensions that are indicated in the plan view of figure 143. All linear dimensions are given in feet. *L* refers to the leg length measured from corner to corner. This includes the length of the strain insulators used at the front and rear poles. *T* refers to the size of the tilt angle in degrees, as previously defined. *H* is the average height of the antenna above average ground level. The harness which ties the antenna corners to the poles usually is attached to the poles at a height 1 to 2 feet above *H*. *W* is the pole spacing along the minor axis of the antenna. *X* is the distance between the rear pole and the point at which the axes cross as measured along the major axis, and *Y* is the distance between the front pole and the point at which the axes cross as measured along the major axis.

Type	Range (miles)	*L* (feet)	*T* (degrees)	*H* (feet)	*W* (feet)	*X* (feet)	*Y* (feet)
A	3, 000+	375	70	65	262. 4	352. 7	355
B	2, 000–3, 000	350	70	60	245. 6	329. 5	331. 8
C	1, 500–2, 000	315	70	57	221. 6	296. 7	299
D	1, 000–1, 500	290	67. 5	55	228	268. 7	271
E	600–1, 000	270	65	53	234	245. 4	247. 7
F	400–600	245	62. 5	51	232	219	221. 3
G	200–400	225	60	50	231	195. 7	198

j. Multiwire Rhombics.

(1) A rhombic antenna will improve in performance if more than a single conductor is used to form each leg. The most common of the *multiwire rhombics* is the three-wire type (fig. 144). The spacing between the three wires forming this antenna increases continuously as the side poles are approached. At this point, a separation of 6 feet exists between adjacent conductors.

(2) When this type is used, the capacitance of the antenna per unit length increases as the separation between the two sides increases. Along the minor axis where the two sides of the antenna are spread farthest apart, the three conductors have their maximum capacitance, and the characteristic impedance of the antenna, therefore, does not vary along its length as it does in a single conductor.

(3) Two advantages occur with the multiwire rhombic. First, the input impedance of the antenna is held at a more constant value over a given range of frequencies. Second, the value of input impedance is reduced somewhat so that a better impedance match to ordinary two-wire line is possible. An ordinary single-wire rhombic antenna designed to operate over a frequency range from 4 to 22 mc may have an input resistance of 850 ohms at 4 mc, 700 ohms at 14 mc, and 625 ohms at 22 mc. If a three-wire rhombic is used instead, it will have an input resistance of 600 ohms plus or minus 50 ohms over this same frequency range. At the same time, a conventional 600-ohm two-wire line can provide practically an ideal impedance match. In addition, the three-wire rhombic has a slight gain (about 1 db) over the single-wire type.

k. Methods of Feeding.

(1) The most common method of feeding a rhombic antenna is by means of a nonresonant two-wire line. With this line, the wide frequency range of the rhombic antenna is not restricted by transmission-line limitations.

(2) When a single-wire rhombic is used, the transmission-line impedance required is

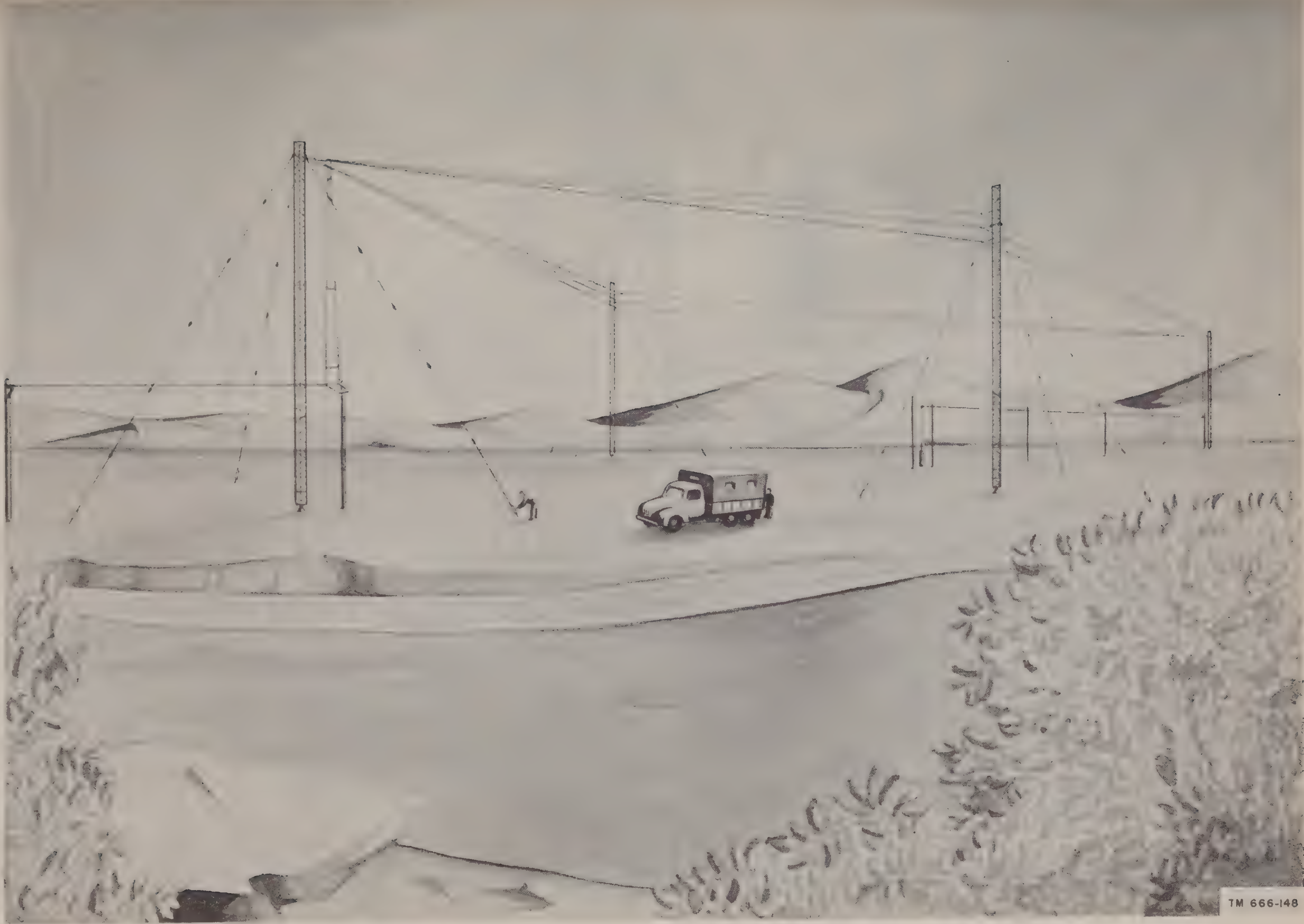

Figure 144. Multiwire rhombic antenna

approximately 700 to 800 ohms. A twc-wire line having such a high value of characteristic impedance would have a fairly wide spacing. As a result of the wide spacing, considerable radiation loss occurs from the line. To avoid this loss, two alternatives are possible. First, a long tapering section of transmission can be used as an impedance-matching section. The spacing between the two conductors is greatest at the end of the section connected to the antenna; therefore the impedance is high enough to match the antenna. The spacing at the other end of the tapered section is least, resulting in a low value of impedance. If the tapered section, known as an *exponential matching section*, is designed to have an impedance of 600 ohms at its small end, ordinary 600-ohm two-wire line can be used between the low-impedance end of the matching section and the transmitter or receiver that is to be connected to the antenna. If the exponential matching section is designed to have a low impedance of 200 to 300 ohms, ordinary four-wire line can be used The second alternative involves the use of 600-ohm two-wire line directly connected to the end of the rhombic antenna. Since the standing-wave ratio is so small, the added loss resulting from a slight mismatch may be low enough to neglect in all cases except those in which peak efficiencies are required. In this method, the coupling to the transmitter may have to be readjusted slightly as the frequency is changed.

(3) When a three-wire rhombic antenna is used, the transmission line impedance required is 600 ohms. It is then necessary only to connect an ordinary two-wire open line having a 600-ohm impedance between the antenna and the transmitter.

l. Lobe Alinement.

(1) When a rhombic antenna is designed according to the information given in the previous charts, it produces maximum output at the supposedly desired vertical wave angle. If the vertical radiation pattern of such an antenna is examined, it will be noted that the maximum output power actually is produced at a vertical angle which is a few degrees less than the desired wave angle. The peak of the maximum radiation lobe falls slightly below the wave angle for which the antenna is designed, as illustrated by lobe *A* in the vertical pattern of figure 145.

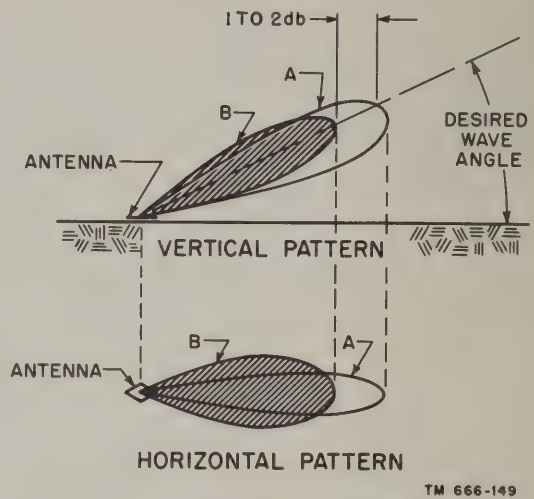

Figure 145. Lobe alinement patterns.

(2) Since no other combination of leg length, tilt angle, and height above ground will produce a rhombic antenna having a greater radiation at the desired wave angle, changing any of these factors would serve to reduce the gain of the antenna at the desired wavelength. It is entirely normal then for the peak of the lobe to occur at a vertical angle that is a few degrees less than the wave angle for which the antenna is designed.

(3) When a rhombic antenna is designed so that the peak of the lobe occurs just at the desired wave angle, the radiation pattern produced is illustrated by lobe *B*. This may be desirable if a somewhat sharper vertical radiation pattern is required along with a somewhat broader horizontal radiation pattern. Some rhombic receiving antennas are designed that produce this type of pattern in order to minimize noise originating near the ground level, and to improve the signal-to-noise ratio of the antenna.

(4) When the pattern illustrated by lobe *B* is required, the *lobe alinement method* is used in designing the antenna. The dimensions given in the previous charts

can be used in the lobe alinement design, except that the length of each leg of the antenna is shortened to three-quarters of the leg length required to produce maximum output. When the lobe alinement method is used, there is a reduction in gain of about 1 or 2 db at the desired wave angle.

m. Ground Effects.

(1) The effect of ground reflections on the radiation pattern of the rhombic antenna is exactly the same as with any horizontal antenna. There is one optimum height above ground at which reflection of radiated energy from the ground acts tc produce maximum radiation at a given wave angle. This is the height which has been given in the preceding charts that show rhombic antenna dimensions.

(2) As the height of the antenna above ground is increased, the wave angle at which maximum radiation occurs is reduced (fig. 146).

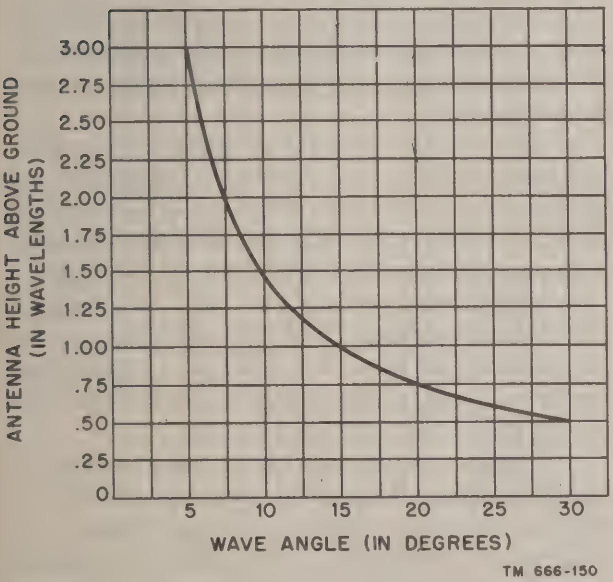

Figure 146. Graph showing variation in wave angle for different antenna heights.

(3) The ground above which the rhombic antenna is installed should be flat and free from obstructions, and it should have a uniform conductivity. If these precautions are not observed, the actual required height of the antenna will be difficult to determine because the actual height required above ground may be considerably different for a given wave angle than is shown in the graph. If a rhombic antenna must be installed above uniformly sloping ground, it is possible to design the antenna in such a way that it compensates for the ground slope. For example, assume that a rhombic antenna is to be designed with a wave angle of 15°, to be erected over ground which has a 5° downward slope toward the front pole of the antenna. The required wave angle can be produced by designing the rhombic to produce a 20° wave angle and mounting the antenna parallel to the ground.

n. Resonant Rhombics.

(1) All of the rhombic antennas discussed so far have been terminated properly so that a unidirectional radiation pattern is produced. In practically every case where a rhombic antenna is referred to, this is the type used. If, however, the terminating resistance is removed from the antenna, a *resonant rhombic* is produced.

(2) Since the resonant rhombic antenna is unterminated, energy traveling from the transmission line to the far end of the antenna is reflected back, and standing waves of voltage and current are set up along the conductors making up the antenna.

(3) The input impedance of such an antenna is no longer in the vicinity of 800 ohms, but instead, is a much higher value. This means that it must be fed by resonant transmission lines, or that impedance-matching sections are necessary. As a result, the antenna cannot be used over a wide frequency range unless extensive retuning of the coupling system occurs along with considerable readjustment of the impedance-matching sections.

(4) The radiation pattern of a resonant rhombic antenna is bidirectional along the major axis of the antenna. If it is desired to transmit or receive in only one direction, the resonant rhombic should not be used. This may interfere with other communication when the antenna is used for reception, since undesired signals and noise will be received from

the direction that is opposite to the desired direction of reception. This lowers the signal-to-noise ratio.

(5) In addition to the undesired major lobe that is produced to the rear of the antenna, the radiation pattern of the resonant rhombic antenna changes considerably when the applied frequency is changed. For example, a certain lobe pattern is produced when the antenna leg is 2 wavelengths, and another pattern is produced when the frequency is raised so that the leg is 2½ wavelengths.

(6) The gain of a resonant rhombic antenna is less than that of a nonresonant terminated rhombic. In the terminated antenna, *less* than one-half the input power is dissipated by the terminating resistance so that *more* than one-half the input power is radiated into space. In the unterminated or resonant rhombic antenna, the radiation divides equally; one-half the available input power is radiated toward the front and one-half toward the rear.

92. Summary

a. Antenna directivity is the ability of an antenna to radiate or receive energy better in some directions than in others.

b. An antenna is said to have gain when it produces a greater field strength at a given distant receiving point than does a standard half-wave antenna. The standard antenna is assumed to be at the same position and height above the earth and is oriented to produce the same polarization.

c. A long-wire or harmonic antenna is one with length greater than a half-wavelength and with current distribution such that there is a reversal of current flow in adjacent half-wave sections.

d. As the length of a long-wire antenna is increased, the gain increases, the lobes of maximum radiation lie closer to the antenna itself, and a greater number of minor lobes is produced.

e. In general, the effects of ground on long-wire antennas are the same as with the basic half-wave antenna.

f. A nonresonant antenna is terminated in a resistance equal to its characteristic impedance. As a result, standing waves no longer exist on the antenna and the radiation pattern becomes unidirectional.

g. The Beverage or wave antenna is a single terminated wire of 2 or more wavelengths, supported on poles a short distance above ground. It is used to transmit or receive vertically polarized ground waves, particularly at low radio frequencies. The operation depends on a process known as wave tilt.

h. The V antenna consists of two horizontal long wires arranged to form a V, and fed at the apex with currents of opposite phase. The radiation pattern is bidirectional along a line which bisects the apex angle.

i. The V antenna can be made unidirectional by connecting 500-ohm noninductive resistors between the far ends of the legs of the V antenna and ground.

j. The half-rhombic antenna is a terminated vertical antenna which has the form of an obtuse-angle V. This antenna works in conjunction with a ground or a counterpoise. An unbalanced transmission line is used to feed the antenna.

k. The radiation from a half-rhombic antenna is unidirectional in the direction of the terminating resistor. A vertically polarized radio wave is produced by this antenna.

l. The rhombic antenna is the highest development of the long-wire antenna. It is used widely for long-distance high-frequency point-to-point communication.

m. The rhombic antenna is useful over a wide frequency range. It is easier to construct and maintain than are other antennas of comparable gain and directivity. The antenna is noncritical so far as operation and adjustment are concerned.

n. Noninductive resistors are used to terminate the rhombic antenna used for receiving or for low transmitter powers. Dissipation lines are used for termination when high transmitter powers are applied to the rhombic antenna.

o. A balanced oscillator can be used to check a rhombic antenna for correct termination. If the oscillator frequency does not change when it is connected to the antenna, no reactance is present at the input terminals of the antenna, and proper termination exists.

p. Standard military rhombic antennas are designed for frequencies from about 4 to 22 mc at ranges from 200 to over 3,000 miles.

q. A multiwire rhombic antenna has a lower and a more constant value of input impedance over a given frequency range than does the single-wire type.

r. Resonant rhombic antennas have bidirectional radiation patterns, high input impedances,

varying characteristics over a given frequency range, and slightly less gain than do the conventional terminated rhombic antennas.

93. Review Questions

a. What is meant by antenna directivity?

b. How is antenna gain measured and in what units is it expressed?

c. Describe a long-wire antenna.

d. In general, what happens to the radiation pattern of an antenna as its length is increased?

e. Calculate the length in feet of a long-wire antenna which is to have two full waves of current distributed along its length at 4 mc.

f. How is radiation resistance affected as the length of a long-wire antenna is increased?

g. How can long-wire antennas be fed?

h. Distinguish between resonant and nonresonant antennas.

i. What is the wave antenna?

j. What value of terminating resistance is required for the Beverage antenna?

k. What is meant by the term *wave tilt*?

l. Describe the V antenna.

m. Discuss the radiation pattern of the V antenna and describe in general how such a pattern is produced.

n. Distinguish between the angles known as the tilt angle and the wave angle.

o. Describe the half-rhombic antenna.

p. What is the radiation pattern of the half-rhombic antenna?

q. Distinguish between the half-rhombic antenna and the obtuse-angle V antenna.

r. Give several methods of supporting the apex of the half-rhombic antenna.

s. Give several advantages of a rhombic antenna.

t. Give some disadvantages of a rhombic antenna.

u. What is the polarization of a radiated wave transmitted by a rhombic antenna? How is this polarization produced?

v. What is the purpose of a dissipation line?

w. How can the termination of a rhombic antenna be checked?

x. Describe the multiwire rhombic antenna and give some advantages of this type over the single-wire antenna.

y. How can rhombic antennas be fed?

z. Give some characteristics of the resonant rhombic antenna.

CHAPTER 5
DRIVEN AND PARASITIC ARRAYS

Section I. INTRODUCTION

94. Multielement Arrays

One means of attaining increased antenna gain and directivity is by use of the multielement array. The long wire, regardless of its length, is looked upon as a single radiating or receiving element; the array is a combination of elements which, considered separately, could be individual antennas. These elements act together or upon each other to produce a given radiation pattern. Various factors influence the choice of methods used to produce high directivity. Whereas the long-wire antenna often is preferred where reception or transmission on more than one frequency is required and where gain or directivity requirements are moderate, the more exact phasing and determination of element lengths in the array make for a more regular radiation pattern. Since fewer minor lobes are developed, available power is concentrated in the major lobe or lobes, and therefore there is greater gain and sharper directivity in the favored direction. In a given available space, the elements of an array can be so arranged as to provide greater gain than a long-wire antenna confined to the same space.

95. Definitions

a. Types of Elements.

(1) As a special arrangement involving new factors and concepts, the array requires special terminology. It is made up of more than one element, but the basic *element* is, generally, the half-wave dipole. Sometimes it is made to have more or less than this length, but the deviation usually is not great.

(2) A *driven element* is connected directly to the transmission line. It obtains its power directly from the transmitter or, in reception, it applies the received energy directly to the receiver. A *parasitic element,* on the other hand, derives its power from another element in the same array. It is placed close enough to the other element to permit coupling and it is excited in this way.

(3) If all of the elements in a given array are driven, the array is called a *driven array.* The term *connected array* sometimes is used to described this type. If one or more elements are parasitic, the entire system usually is considered to be a *parasitic array.*

(4) A parasitic element sometimes is placed so that it will produce maximum radiation (in transmission) from its associated driver, and it operates to reinforce energy going *from* the driver *toward* itself. When so used, the parasitic element is referred to as a *director.* If a parasitic element is placed on the other side of the driven element and causes maximum energy radiation in the direction from itself toward the driven element, it is called a *reflector.*

b. Directivity. Multielement arrays frequently are classified as to their directivity. A *bidirectional array* radiates in both opposite directions along the line of maximum radiation. A *unidirectional arra* radiates in only one direction.

c. Types of Arrays.

(1) Arrays have been described above with respect to their radiation patterns and the types of elements which comprise them. It is useful, however, to identify them by the physical placement of the elements and the direction of radiation in respect to these elements. Generally speaking, the term *broadside array* designates any one in which the direction of maximum radiation is perpendicular to the plane containing the elements. In practice, however, this term is confined to those arrays in which the elements

themselves are also broadside or parallel in respect to each other.

(2) A *collinear array* is one in which all the elements lie in the same straight line. The direction of propagation is broadside to the array.

(3) An *end-fire* array is one in which the principal direction of radiation is along the plane of the array itself.

(4) Sometimes a system is used incorporating characteristics of more than one of the three types mentioned above. For instance, some of the elements may be collinear, others may be parallel. Such an arrangement often is referred to as a *combination array* or an *array of arrays*, although, since maximum radiation occurs at right angles to the plane of the array, the term *broadside array* could be used.

d. Front-To-Back Ratio. The *front-to-back ratio* is the proportion between energy radiated in the principal direction to the energy radiated in the opposite direction.

96. Phasing

a. Coupling in Space.

(1) Various reflected and refracted components of the propagated wave create certain effects of reinforcement and cancelation. At certain points distant from the transmitter, some of these components meet in space. Reception at these points is either impaired or improved. If the different components arrive at a given point in the same phase, they add, making a stronger signal available, and if they arrive out of phase, they cancel.

(2) Effects of this kind are caused by factors operating some distance from the point of transmission. It is possible to cause somewhat similar effects to occur at the transmitting point itself. Consider antennas A and B, figure 147. They are two dipoles perpendicular to the plane of the page and are, therefore, shown as points. They are spaced a quarter-wavelength apart at the operating frequency. The radiation from either antenna, operating alone, is uniform in all directions in this plane. Consequently, the pattern produced by each antenna is a circle with the antenna at its center. Suppose, however, that current is being fed to both antennas from the same transmitter, but in such a way that the current fed to antenna B lags the current in antenna A by 90°, or the time required for a quarter of a cycle. Energy radiating from antenna A toward receiving location X reaches antenna B after ¼ cycle of operation. When it reaches antenna B, it meets the radiation from that antenna toward X in exactly the same phase. Therefore, radiation from both antennas add, and propagation toward X is strong. Radiation from antenna B toward receiving location Y reaches antenna A after ¼ cycle. Since the energy in antenna A was ¼ cycle behind that of antenna B to begin with, the radiation from both antennas toward receiving point Y are exactly 180° out of phase when they join. As a result, they cancel and no radiation occurs toward Y. At receiving points away from the line of radiation, indicated by the broken arrows, there are phase differences not quite so pronounced as to produce complete addition or outright cancelation. The over-all effect is indicated by the radiation pattern shown. The physical phase relationship caused by the quarter-wave spacing between the two elements,

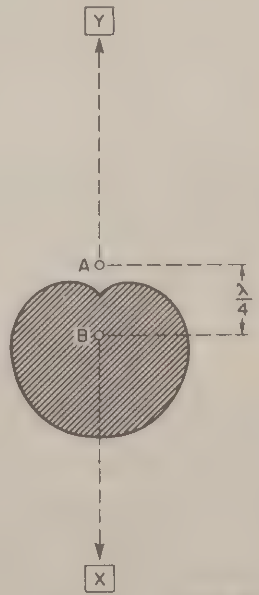

Figure 147. Phasing of antennas in space.

as well as the phase of the currents in them, has acted to change the radiation pattern.

b. Stub Phasing.

(1) In the case just discussed, it was mentioned that the currents fed to both antennas from the same transmitter were 90° out of phase. No explanation was given of the manner in which this is done. Sections of transmission line, called stubs, frequently are used for this purpose. These can be adjusted to produce any desired phase relationship between connected elements.

(2) When two collinear half-wave elements are connected directly so that their currents are in the same phase, the effect is that of a full-wave antenna (*A* of fig. 148). The current in the first half-wavelength is exactly 180° out of phase with that in the second half-wavelength, as shown. This is the opposite of the desired condition. (In addition to the current waveform, arrows are used to indicate the direction of current flow which is more convenient for determining the phase of current on more complicated arrays.)

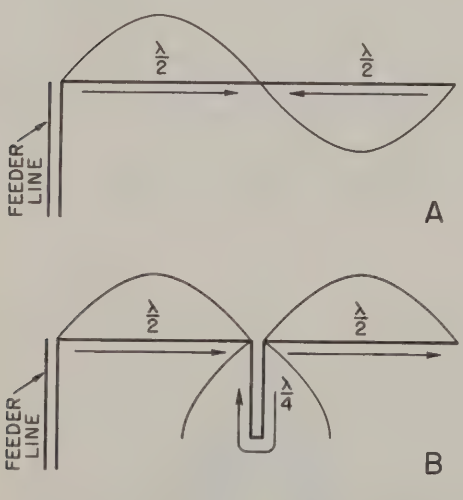

Figure 148. Phasing of connected elements.

(3) When the elements are connected by a quarter-wave stub as in *B*, current travels down one side of the stub and up the other. It travels a distance of a half-wavelength in the stub itself, and, as a result, it moves through ½ cycle of change. When the current reaches the next element, it is in the desired phase. Since the current in one side of the stub is equal and opposite to current on the other side, the fields produced cancel, and, consequently, there is no radiation from the stub itself.

97. Mutual Impedance

a. Definition.

(1) The impedance of an antenna at any point can be calculated by Ohm's law from the current and voltage at that point, but, in an isolated antenna element this impedance is known as self impedance. When another element is nearby the impedance is changed. Suppose that in figure 147, driven element *A* is parallel to and near unconnected (parasitic) element *B*. During operation, radiation from antenna *A* reaches antenna *B*, inducing current in the latter. The field associated with this current in turn influences antenna *A*. In other words, in addition to the current supplied to antenna *A* from the source, current is induced by antenna *B*. The current and voltage relationship at a given point on antenna *A* now will be different from the relationships that exist when no other element is nearby. Therefore, the impedance, calculated from current and voltage, will be different also.

(2) When an antenna element is operating in association with other elements, a different value of impedance is measured which is referred to as its actual impedance. *Mutual impedance* is the impedance that results from the coupling between the two elements which is responsible for the difference between the self impedance and the actual impedance of a given element.

b. Current Amplitude. When two parallel antenna elements are close together, the current induced in one by the other will be great. If one of these elements is driven and the other is not, the current in the driven element then is the current supplied by the transmitter simply added to that induced by the parasitic element, if there is no phase difference. Mutual impedance permits

greater gain in the array than in a single antenna, although there is no actual increase in transmitter power, and mutual impedance acts to decrease the actual impedance, since the current in the driven element has increased. As the parasitic element is moved farther from the connected element, there is less coupling. As a result, less current is induced in the driven element, and less gain is produced. The effect of mutual impedance decreases and the actual impedance of the driven element approaches its self impedance.

c. Current Phase.

(1) The amplitude of the induced current is not the sole factor determining gain. In practice, antenna gain can be reduced to a smaller value even as the amplitude of the induced current becomes greater. This occurs when the induced and original currents are 180° out of phase, at which time mutual impedance acts to increase the actual impedance, since the current in the driven element is reduced.

(2) The distance between two elements in terms of wavelength at the operating frequency determines the relative phase between them. Then, cancelation and reinforcement of signal resulting from phase difference are particularly noticeable when the distance between the two elements is a fraction of a wavelength.

(3) Consider an antenna that is cut to resonance at a given frequency. Since the reactive components cancel out, its self impedance is purely resistive. When this antenna works with another element (parasitic) so that the current induced back into the former is exactly in phase with the original, there is increased amplitude with no change in phase. Although the actual impedance has decreased, it still is purely resistive. When the induced current is exactly 180° out of phase with the original, there is decreased amplitude but still no change in phase. Again, the actual impedance remains resistive, although it is now greater than the self impedance. When the induced current is *not* exactly in phase or 180° out of phase with the original current, the phase of the total current shifts in respect to voltage. This change of relative phase between current and voltage indicates that a reactive effect is present. As a result of this reactive effect, the antenna can be tuned off resonance by the presence of another element. It is correct, therefore, to say that mutual impedance may contain both reactive and resistive components.

(4) If a resonant antenna associated with a parasitic element is tuned off resonance, the phase of the current induced in the parasitic element is shifted. Therefore, the phase of the current induced back into the resonant antenna also is shifted. In other words, the tuning of a parasitic element also affects the reactive component of mutual impedance.

Section II. DRIVEN ARRAYS

98. General

a. Description.

(1) Driven arrays form a major subdivision of multielement arrays. The distinctive property of the driven array is the fact that *all* of the elements used derive their power from the same source, the transmitter. This property differentiates this group from the other major class of multielement systems, the parasitic arrays, in which one or more elements are driven directly whereas others are excited by these driven elements.

(2) The driven array is preferred when high-power transmission is desired in addition to high directivity, because the driven array introduces less over-all power loss than occurs in other multielement systems where loss of energy is caused by insufficient coupling between elements.

b. Problems of Feeding.

(1) Special attention must be given to certain factors involved in feeding driven arrays. Current distribution is one of these, and phasing is another. For example, in an array consisting of four elements, the same amount of power must be fed to each element, and the current in each element must be in phase with the current in each of the other

three. Care must be exercised to maintain these conditions as exactly as possible. If deviations exist, undesired cancelations and reinforcements occur. As a result, undesired lobes can be introduced into the radiation pattern. Desired lobes can be emphasized or deemphasized, but beam width and directivity are affected and the advantages sought in the use of a given array can be nullified in this way.

(2) Care must be taken in interconnecting the elements of an array since radiation from sections of transmission line used for interconnecting can reduce effectiveness. Pick-up by these sections when the array is used for receiving may cause interference.

99. Directivity

a. Directivity and Gain. The directivity of an antenna or an array can be determined by examining its radiation pattern. In an array propagating a given amount of energy, greater radiation takes place in certain directions than in others. The elements in the array can be manipulated in such a way that they change this pattern and distribute it more uniformly in all directions. They can be considered as a group of antennas, fed from a common source, facing in different directions. On the other hand, the elements can be disposed in such a manner that the radiation will be focused or concentrated in a single direction. With no increase in power, the amount of radiation in a given direction is greater. Since there is no increase in the input power, this is achieved at the expense of gain in other directions.

b. Directivity and Interference.

(1) There are many applications in which sharp directivity is desirable although there is no need for added gain. Examine the physical disposition of the units shown in figure 149. A_T and B_T are transmitters. It is desired that they send information to receivers A_R and B_R, respectively, along the paths shown by the solid arrows. The distance between A_T and A_R, or between A_T and B_R, is not so great as to require high-power transmission. If the antennas of A_T and B_T propagate well in all directions, however, there is some pick-up of A_T at B_R and of B_T at A_R, as shown by the broken arrows. This effect is emphasized if the receiving antennas intercept energy well in all directions.

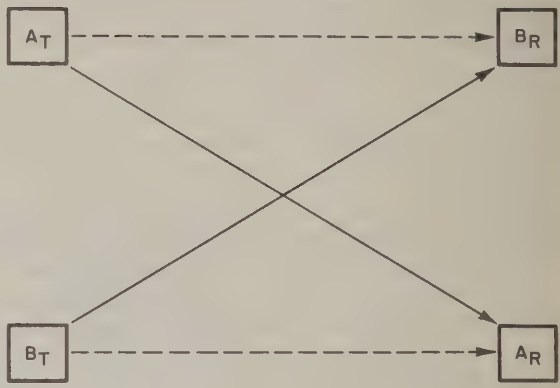

Figure 149. Directivity and interference.

(2) The use of highly directional arrays as radiators from A_T and B_T, beamed along the paths of the solid arrows and with low radiation along the paths of the broken arrows, tends to solve the problem. With this arrangement, considerable power is available from the desired sources at the respective receiving points, and little power is available from the unwanted sources. Further improvement along these lines is obtained by the use of narrowly directed arrays as receiving antennas at locations A_R and B_R.

(3) The effect of this arrangement is to select a desired signal while discriminating against an interfering signal. The same approach can be used to overcome types of radiated interference other than unwanted transmissions. In such cases, it is more important to *prevent* radiation in certain directions than it is to produce greater gain in other directions.

(4) The differences between the single-element antenna and the array are illustrated in figure 150, in which A gives the relative field strength pattern for a horizontal polarized single antenna, and B shows the horizontal radiation pattern for one particular array. The antenna at A radiates fairly well in the desired direction, toward receiving point 1 It radiates equally well, however, toward

point 2 , although no radiation is desired in this direction. If the antenna at *B* is used in the same situation, it radiates strongly to point 1 but very little in the direction of point 2 . Consequently, more satisfactory operation results.

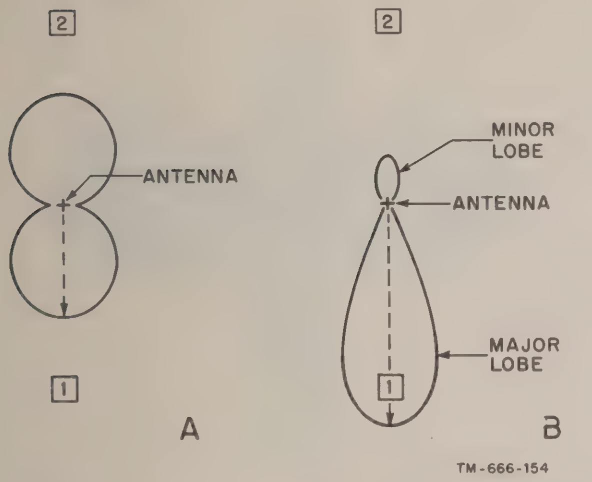

Figure 150. Single antenna versus array.

c. Major and Minor Lobes. The pattern shown in *B* has radiation concentrated in two lobes. The radiation intensity in the *B* 1 lobe is considerably stronger than in the *B* 2 lobe. *B* 1 is called a *major lobe*, *B* 2 a *minor lobe.* Since the complex radiation patterns associated with arrays frequently contain several lobes of varying intensity, it is convenient to adopt appropriate terminology. In general, major lobes are those in which the greatest amount of radiation occurs. Minor lobes are those in which the radiation intensity is less.

100. Main Systems

Within the family of driven arrays, there are three basic types—collinear, broadside, and end-fire. Any driven array is one of these types or represents a combination of more than one of them.

a. Collinear Arrays.

(1) Radiation from a half-wave antenna is represented by two broad lobes in opposite directions. A method of connecting two such elements arranged in a straight line to operate in the same phase is shown in *B* of figure 148. Basically, the pattern radiated by this latter combination is similar to that produced by the single dipole. The addition of another radiator, however, tends to intensify the pattern. A comparison of the two patterns in figure 151 shows that each consists of two major lobes in opposite directions along the same axis, *Q* to *Q1*. Along this line of maximum propagation, radiation is stronger with the added element. Moving toward the *PP1* axis, this reinforcing effect falls off. The pattern in *B* is sharper or more directive. This is the same as saying that gain along the line of maximum energy propagation is increased, whereas the beam width is reduced. As more elements are added, the effect is heightened, although unimportant minor lobes are added.

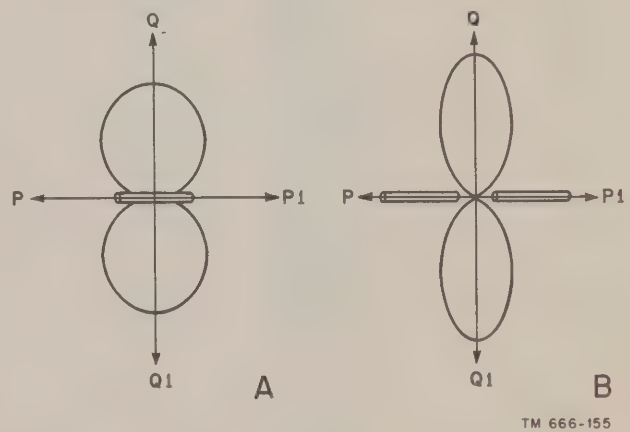

Figure 151. Single half-wave antenna versus two half-wave antennas in phase.

(2) If all of the elements in a driven array lie in a single straight line, the array is known as a collinear array. The currents in the various elements are always in the same phase. The elements are connected to each other by stubs adjusted to assure proper phasing. These elements usually are a half-wavelength, but greater lengths also are used. To assure proper phasing, the connecting sections are a quarter-wavelength. However, when the length of the elements is increased, the length of the connecting sections must be decreased.

(3) A method using four collinear elements is shown in figure 152. The arrows in *A* (side view) illustrate the distribution and

relative phase of current in the array. At the frequency for which it is designed to operate, any collinear array, regardless of the number of elements, produces a bidirectional pattern (top view in *B*) with axis perpendicular or broadside to the line of the elements.

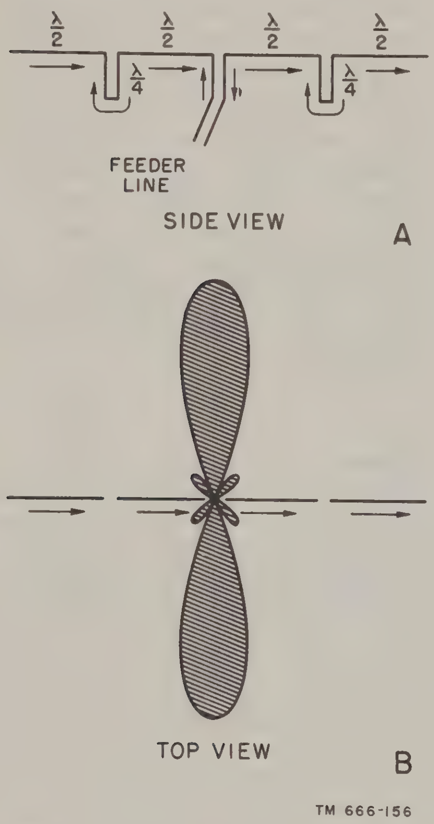

Figure 152. Typical collinear array.

b. Broadside Arrays.

(1) Figure 153 shows an end view of two parallel half-wave antennas, *A* and *B*, operating in the same phase and located a half-wavelength apart. At a given point, *P*, far removed from the antennas, they appear as a single point. Energy radiating toward *P* from antenna *A* starts out in phase with energy radiating from antenna *B* in the same direction. Propagation from each travels over the same distance to point *P*, arriving there in the same phase. In other words, the antennas reinforce each other in this direction, making a strong signal available at *P*. Field strength measured at that point is greater than it would be if the total power supplied to both antennas had been fed to a single half-wave dipole. Radiation toward point *P1* is built up in the same manner.

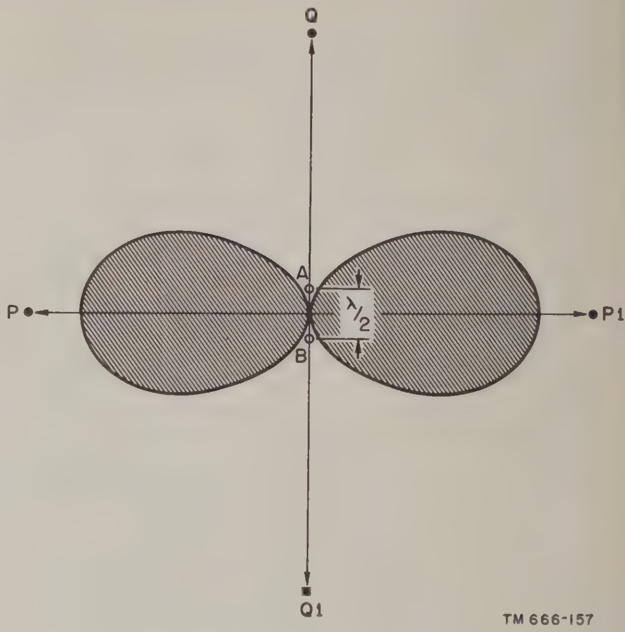

Figure 153. Parallel elements in phase.

(2) Consider next a wavefront traveling toward point *Q* from antenna *B*. By the time it reaches antenna *A*, a half-wavelength away, half a cycle has elapsed. Therefore, energy from *B* meets the energy from antenna *A* 180° out of phase, with the result that energy from the two sources moving toward point *Q* cancels. In like manner, radiation from antenna *A* traveling toward point *Q1* meets and cancels the radiation from antenna *B* in the same direction. As a result, there is little propagation in either direction along the *Q* to *Q1* axis, most of it being concentrated in both directions along the *P* to *P1* axis. When both antenna elements are fed from the same source, the result is the basic broadside array.

(3) When more than two elements are used in a broadside arrangement, they are all parallel and in the same plane, as shown in figure 154. Current phase, indicated by the arrows in *A*, must be the same for all elements. The radiation pattern, shown in *B*, is always bidirectional. This pattern is sharper than the one shown in the previous illustration be-

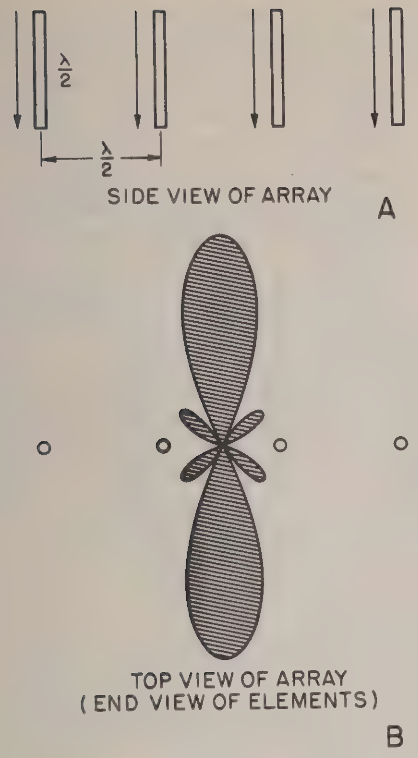

Figure 154. Typical broadside array.

cause of the addition of two elements. Directivity and gain depend on the number of elements and on the spacing between them.

c. End-Fire Arrays.

(1) The radiation pattern for a pair of parallel half-wave elements is shown in *A* of figure 155, fed 180° out of phase. The elements shown are spaced a half-wavelength apart, but, in practice, smaller spacings are used, for reasons to be discussed later. Radiation from elements A and B traveling toward point *P* starts out with the 180° phase difference. Moving the same distance over approximately parallel paths, the respective wave fronts from these elements maintain the 180° phase difference. In other words, there is maximum cancelation in the direction of *P*. The same condition holds true for the opposite direction. The *P* to *P1* axis, which is the line of propagation in the case of the broadside array, becomes the line of least radiation in figure 156, where the end-fire principle is used.

(2) Consider what happens along the *Q* to *Q1* axis. Energy radiating from element B toward *Q* reaches antenna *A* about half a cycle or 180° after it leaves its source. Since radiation from element

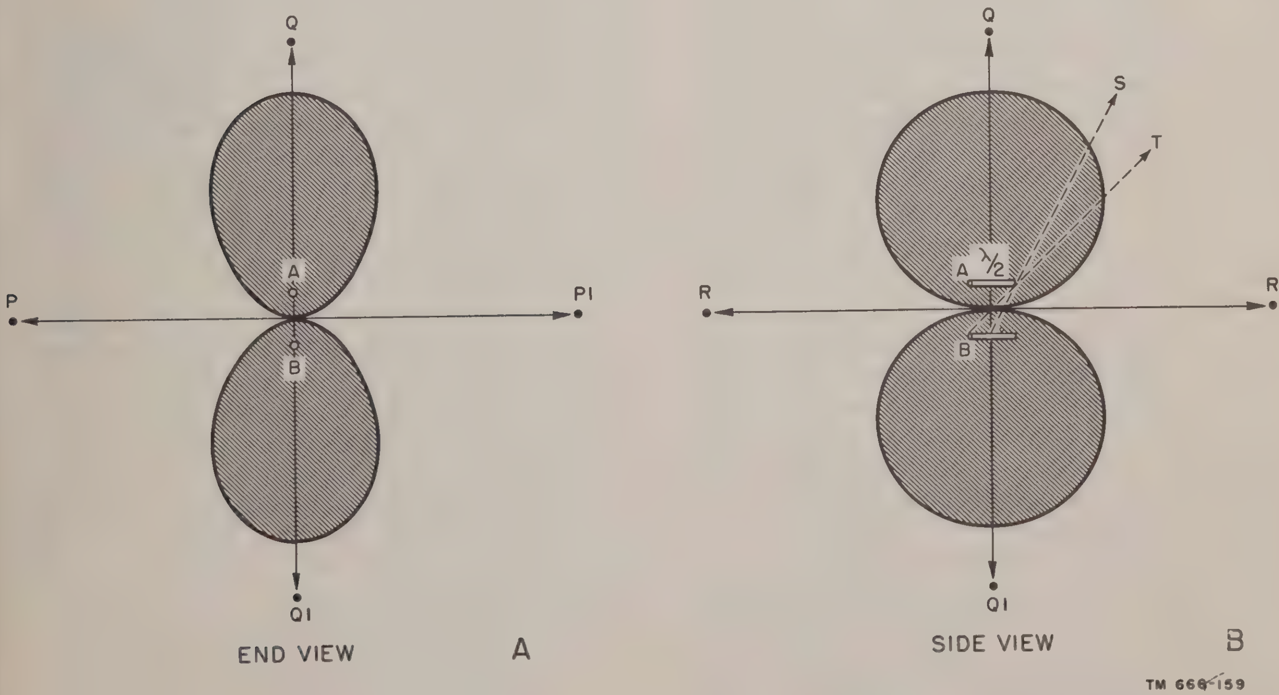

Figure 155. Parallel elements 180° out of phase.

A is originally 180° out of phase, the wave fronts are now approximately in the same phase moving toward *Q*, and they reinforce. Similar reinforcement occurs along the same axis toward *Q1*.

(3) In the example above, a bidirectional pattern is developed, which is not always true in end-fire operation. Figure 147 is another application of the end-fire principle where elements are spaced a quarter-wavelength apart and phased 90° from each other to produce a unidirectional pattern. The importance of spacing and current phasing is apparent.

(4) In *A*, figure 155, elements A and B are seen perpendicular to the plane represented by the paper and, therefore, only the ends of the antennas appear. If the antennas are rotated a quarter of a circle in space around the *Q* to *Q1* axis so that they are seen in the plane of the elements themselves, as shown in B, the *P* to *P1* axis, now perpendicular to the page, is not seen as a line. The axis, *R* to *R1*, now seen as a line, is perpendicular to *P* to *P1* as well as to *Q* to *Q1*. The end-fire array is directional in this plane also, although not quite so sharply. The reason for the greater broadness of the lobes can be seen by following the path of energy radiating from the midpoint of element B toward point *S*. This energy passes the A element at one end after traveling slightly more than the perpendicular distance between the dipoles. Energy from these, therefore, does not combine in exact phase toward point *S*. Although maximum radiation cannot take place in this direction, energy from the two sources combines closely enough in phase to produce considerable reinforcement. A similar situation exists for wave fronts traveling toward *T*, but the wider angle accounts for a greater phase difference with a resulting decrease in the strength of the combined wave.

(5) To sum up, end-fire arrays consist of half-wave elements in which the currents are 180° out of phase. Directivity is off either or both ends of the array (along the axis of the array), as shown by the broken arrows in figure 156; hence the term *end-fire* is used. The pattern may be dibirectional or unidirectional, depending on the distance between elements and the relative phase of the currents flowing in them. Gain also depends on these two factors. Directivity is achieved in two planes, but is sharper in one than in the other. The pattern in the plane shown in *A* is sharper than that for the plane in *B*.

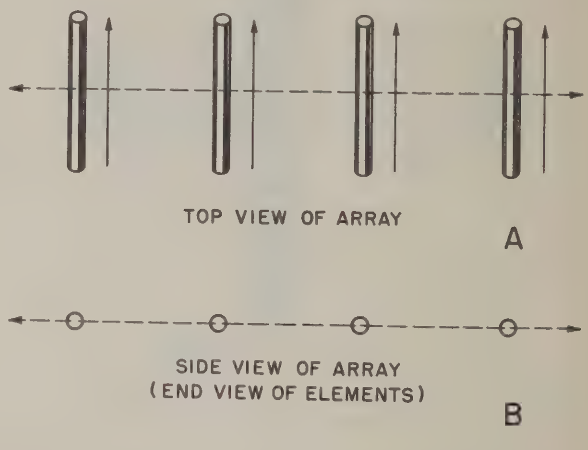

Figure 156. Typical end-fire array.

101. Collinear Arrays

a. General Description.

(1) The simplest type of collinear array is the center-fed "two half-waves in phase" arrangement shown in *A*, figure 157. The array in *B* also consists of two dipoles, but end feeding is used here, making necessary the use of a phase-reversing quarter-wave connecting stub between the elements. For purposes of feeding, notice that both arrangements mentioned so far are fed at voltage loops. In this connection, the terms *end-fed* and *center-fed* are likely to be misleading. In *C*, a three-element array is used. In *D*, the three-element array is center-fed with feed being introduced at the midpoint of one element. This is an instance of current feed. The system shown in *E* is the frequently used, balanced four-element collinear array.

(2) More than four elements seldom are used, because, as more elements are added farther from the point of feeding, accumulated losses cause the farthest ele-

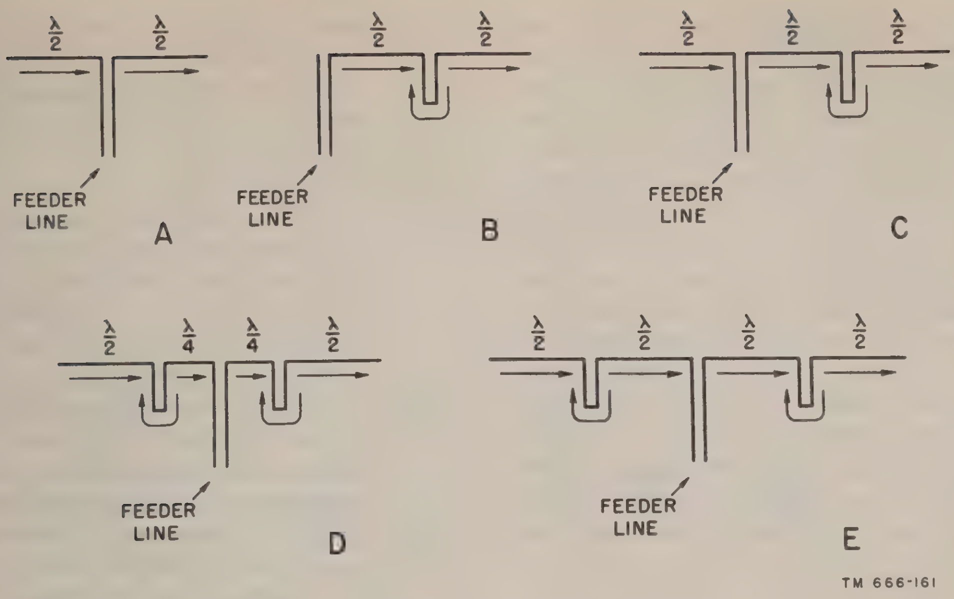

Figure 157. Representative collinear arrays.

ments to have less current than the nearest ones. This introduces an unbalanced condition in the system, which impairs its efficiency. Space limitations often provide another reason for limiting the number of elements. Since this type of array is in a single line, rather than in a stacked arrangement, the use of too many elements results in an antenna of several wavelengths.

(3) The characteristic radiation pattern of a given array is obtained at the frequency or band of frequencies at which the system is made resonant; but the desired gain and directivity characteristics are lost when the antenna is not used at or near this frequency. The array then tunes sharply and acts as a simple long-wire antenna. However, it will be shown later that collinear arrays have higher radiation resistances than other types. If the resistance is higher, the Q is lower, and the antenna does not tune as sharply. A collinear antenna, then, is more effective when used off its tuned frequency than an end-fire array. This feature is considered when transmission or reception is to be over a wide frequency band. When more than two elements are used, this advantage largely disappears.

b. Length and Phasing.

(1) Although the half-wavelength is the basis for the collinear element, greater lengths often are used. Effective arrays of this type have been constructed in which the elements are 0.7 and even 0.8 wavelength which provides efficient operation at more than one frequency or over a wider frequency range. One frequent variation uses elements cut to 0.64 wavelength. Whatever length is decided on, it is important that all of the elements in a particular array closely adhere to it. If elements of different lengths are combined, current phasing and distribution are changed, throwing the system out of balance and seriously affecting the radiation pattern.

(2) When the elements are made longer, it is necessary to decrease the size of the connecting stubs in order to maintain proper current phase (*A* of fig. 158). The arrows indicate the phase reversal at every half-wavelength. The first element, at the left, has current flowing in one direction for a quarter-wavelength and current flowing in the opposite direction for the remaining half-wavelength. The eighth-wavelength stub does not allow for a complete reversal of current flow. Instead, the change in direction takes place a quarter-wavelength along the length of the second element, making the distribution in this

length exactly like that in the first element. The current wave forms are shown to make this clear. In *B*, another possible distribution is shown for the same two elements. In each case, there are half-wave sections of both elements in the same phase. The distance between one half-wave section as it exists on one element in the array and the corresponding similarly phased half-wave section on the adjacent element (the distance from 1 to 2) is greater in each of these examples than it is when the elements themselves are exactly 1 half-wavelength long and are separated by quarter-wave connecting stubs. This affords an advantage, which will be discussed later.

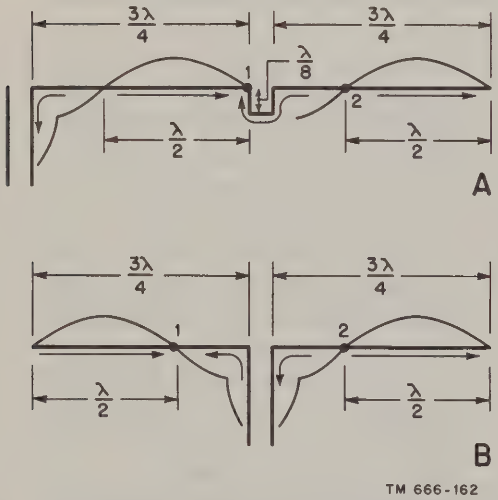

Figure 158. Collinear elements longer than a half-wavelength

(3) The length of the basic half-wave element used in this type of array and all driven arrays is determined from the following corrected formula:

$$L=\frac{468}{f}$$

where L is the length in feet, and f is the frequency in megacycles. The same formula applies whether the elements are of rigid construction or are made up of lengths of wire. For wire arrangements, the formula takes into account the capacitive effects of spacers and supporting insulators. When rigid elements are used, the greater thickness of these elements can be considered to have much the same effect.

c. Gain and Directivity.

(1) *Number of elements.* As a general principle, increasing the number of elements in a collinear array also increases gain and directivity. Figure 159 shows the change in shape of the radiation patterns of various collinear arrays. The increase in gain produced is not shown in these patterns. Parts *A*, *B*, and *C* represent respectively the radiation patterns of typical two-, three-, and four-element arrays, all patterns being shown broadside to the line of the elements. There is a practical limit, however, to the number of elements. Availability of space is one limiting factor, the danger of unbalancing the array is another, and the third is a nonlinear gain over one array element less, which is shown in the chart below. The figures are for collinear arrays using half-wave dipoles with negligible spacing between the elements. Adding a third dipole to the basic two-element array provides an additional gain of 1.5 db. A fourth dipole affords another 1.2 db of gain; a fifth element provides only 0.8 db of additional gain. As the number of elements is increased, the added gain thus achieved does not go up proportionally. When greater gain is important in a particular installation, good practice indicates the use of some type of array other than the collinear. The addition of elements to a collinear array increases loss resistance, both in the phase-reversing connecting stubs and in the elements themselves. Power consumed by this resistance is not radiated. The addition of dipole sections tends to unbalance, because some of the energy fed to the array is radiated by the elements nearest the point of feed before it can reach the sections farthest from this point. Consequently, the end elements radiate less than the center segments.

Number of elements	Power gain (db)	Gain over array using one element less (db)
2	1. 8	
3	3. 3	1. 5
4	4. 5	1. 2
5	5. 3	0. 8

(2) *Spacing.*

(*a*) The lower relative efficiency of collinear arrays of many elements compared with other multielement arrays relates directly to spacing and mutual impedance effects. Mutual impedance is an important factor to be considered when any two elements are parallel and are spaced so that there is considerable coupling between them. Between collinear sections there is very little mutual impedance, but, where it does exist, it is caused by the coupling between the ends of adjacent elements.

(*b*) Constructional problems, especially where long lengths of wire are involved, frequently make it necessary to place the ends of the elements close together. Another limit on the spacing is the physical construction of the connecting stub. If the width of the stub is made too great or if the stub is not connected properly between the segments, undesired radiation results. When rigid elements are used at the higher frequencies and correspondingly shorter wavelengths, the advantages of optimum spacing can be realized in a practical way. The graph of figure 160 shows the relationship of spacing between adjacent ends and gain for two half-wave collinear elements.

(*c*) Spacing often is referred to as the distance between the center points of adjacent elements rather than the absolute distance between their ends. If the spacing is given as 3 quarter-wavelengths, center to center, where half-wave dipoles are involved it is the same as saying that the space between their ends is slightly greater than a quarter-wavelength. It is slightly greater because end effect accounts for

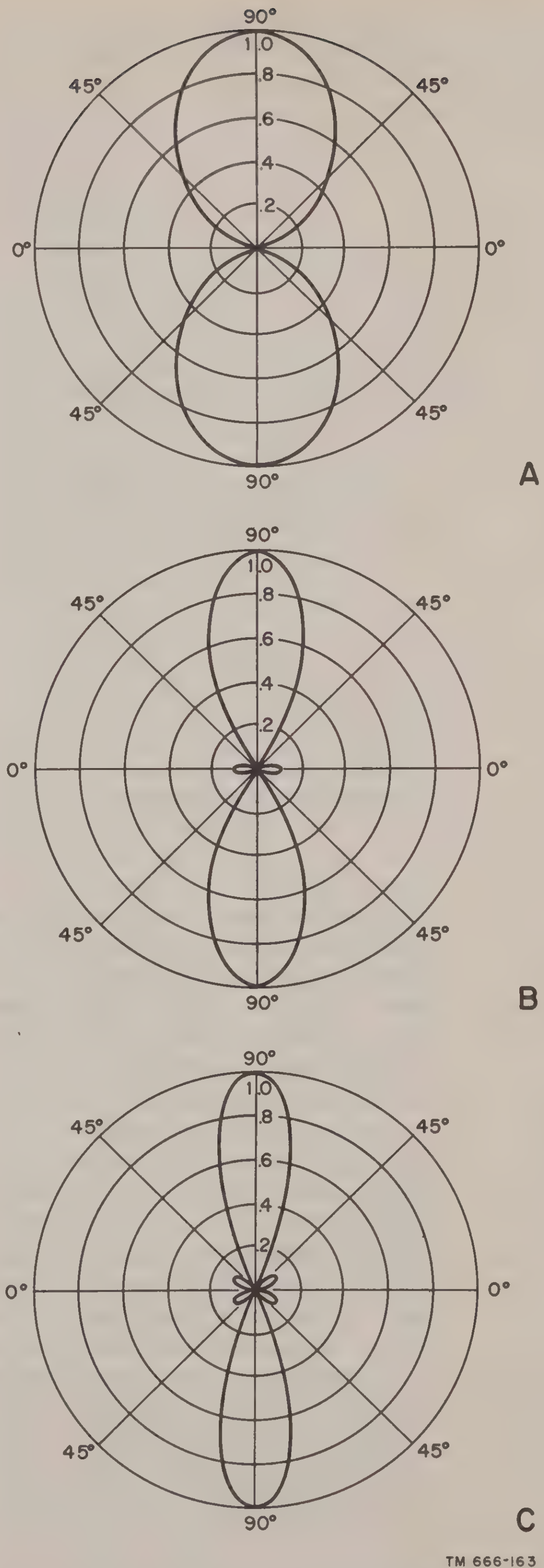

Figure 159. Free-space patterns for collinear arrays.

the dipoles being shorter than a half-wavelength.

(*d*) The effects of spacing, and the advantages of proper spacing, can be demonstrated by some practical examples.

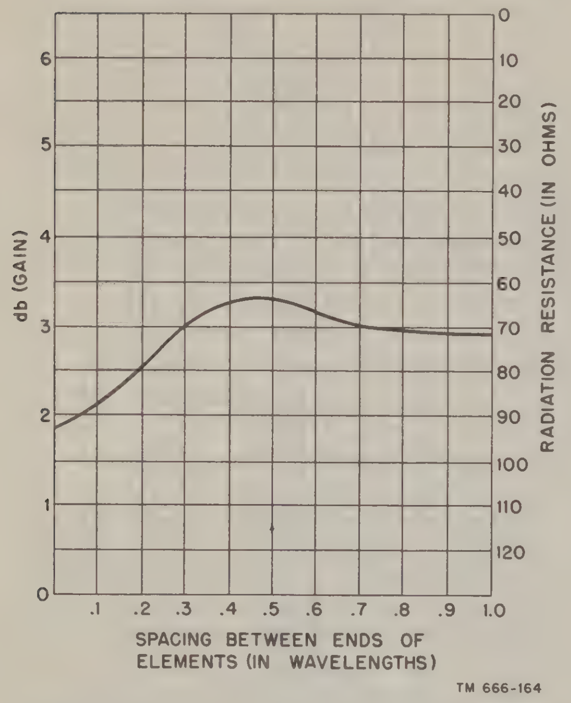

Figure 160. Spacing and gain for collinear elements.

A collinear array consisting of two half-wave elements with half-wavelength spacing between centers has a gain of 1.8 db. If the ends of these same dipoles are separated so that the distance from center to center is 3 quarter-wavelengths, and they are driven from the same source, the gain increases to 3.2 db. Reference to the chart above shows that a three-dipole array with negligible spacing between elements gives a gain of 3.3 db. In other words, when two elements are used with wider spacing, the gain thus obtained is approximately equal to the gain obtainable from three elements with close spacing. The spaced array permits simpler construction, since only two dipoles are used, and occupies less space. Reference to the graph of figure 160 shows that maximum gain is reached when spacing between the elements is in the vicinity of 0.4 or 0.5 wavelength. However, constructional problems usually dictate smaller practical spacing.

(*e*) Optimum spacing is difficult to arrange in general, and it is particularly a problem when wire elements rather than rigid elements are used at frequencies having fairly long wavelengths. The only spacing between wire elements generally is provided by the insulator between lengths of wire. There is a practical way, however, of achieving the desired effects of increased spacing without actually increasing the physical distance between the ends of the elements. This is done by making the elements themselves longer, which, although it gives the effect of increased spacing, simplifies construction.

d. Feeding Methods and Adjustment.

(1) *Feeding.* Collinear systems usually are fed at an end point between half-wave elements. Since there is a voltage loop and a current null at such a point, the impedance is relatively high, generally around 1,500 ohms. This impedance, together with the low Q of collinear arrays resulting from the relatively high radiation resistance and consequently lower standing-wave ratio, permits a certain amount of mismatch between the feed line and the antenna. For this reason, flat or nonresonant lines are used widely. The use of the flat line provides another advantage if operation is to be on more than one frequency. The permissible degree of mismatch makes it possible to feed a conventional collinear array with open-wire 600-ohm line in which the standing-wave ratio is 2 to 1 or less. In the less frequently encountered case of the current-fed collinear array (when feed is introduced at the center of one element as it sometimes is with the three-element arrangement to maintain balance), impedance at the feed point closely matches 300-ohm line. The use of 600 ohm line also is permissible here, since the standing-wave ratio is still low. Conventional matching devices can be used, however, if it is desired to connect line and antenna.

(2) *Adjustment.* When only two elements are

used with center feed (between the elements), both lengths must be the same and no great problem exists. When more than two elements are involved, adjustment to resonance should begin with the two connected directly to the feed line and with a constant input to the antenna. The length thus obtained may not correspond exactly to the calculated length. It is important, however, that all elements be of the same length to maintain balance. Once this measurement is determined, cut all elements to be used to the same size. The length of the phasing stubs must be determined by formula for the particular type of line used. Cut them slightly longer than calculation indicates. Effective adjustment for proper phasing can be made only during actual assembly. One additional element with its associated stub is added to one side of the basic two-element array. Next, using a shorting bar, determine the point along the stub at which current is maximum. Cutting at this point makes the length of the stub correct. If the array is not to be fed at its center (with respect to all its elements), add one element at a time with its associated stub. If the array is balanced, add two elements at a time, one to either end. In either case, the procedure just mentioned for phasing the stub or stubs is repeated. After the addition of each new element or pair of elements, the entire system must be checked to make certain that it is tuned properly. If a matching stub is used between antenna and line, it must be adjusted for maximum current also, but only after all elements have been connected and phased properly.

102. Broadside Arrays

a. General Description. Physically, a broadside array looks like a ladder. When the array and the elements in it are polarized horizontally, it looks like an upright ladder. When the array is polarized vertically, it looks like a ladder lying on one side. Horizontally polarized arrays using more than two elements are common, since the requirement that the bottom of the array be an appreciable distance above the earth presents constructional problems. Compared with collinear systems, arrays of this kind tune sharply, and therefore, lose efficiency rapidly when not operated on the frequencies for which they are designed. The higher Q resulting from the lower radiation resistance is responsible for this.

b. Gain and Directivity.

(1) *Spacing.* The physical disposition of dipoles operated broadside to each other allows for much greater coupling between them than can occur between collinear elements. Moving the parallel antenna elements closer together or farther apart materially affects the actual impedance of the entire array and the over-all radiation resistance as well. This critical effect of spacing may be seen from the graph of figure 161, in which the gain of two broadside elements is plotted against the spacing between them. Compare this with a similar graph for two collinear dipoles (fig. 160). Both curves follow the same general path, but the one for broadside elements is much sharper. For collinear elements, since spacing is varied between 0 and 1.0 wavelength, there is a variation in gain of about 1.5 db. For broadside dipoles, the range of variation in gain is nearly 5 db over the same range of spacings. In addition, the optimum spacing as far as gain alone is concerned occurs at a slightly greater spacing than is the case for collinear dipoles, approximately 0.65 wavelength. However, to simplify phasing and feeding, half-wave spacing generally is used. Less than 1 db of gain is sacrificed by this expedient. Where more elements are used, the gain sacrificed is even greater. However, it can be recovered easily since the space saved can be used to accommodate one or more additional elements. As the spacing between broadside elements is increased, the effect on the radiation pattern is to sharpen the major lobes. When the array consists of only two dipoles exactly a half-wavelength apart, there are no minor lobes at all. Increasing the distance between the elements beyond that point, however, tends to throw off the phase relationship between the original

current in one element and the current induced in it by the other element. The result is that, although the major lobes are sharpened, minor lobes are introduced even with two elements. These, however, are not large enough to be of consequence.

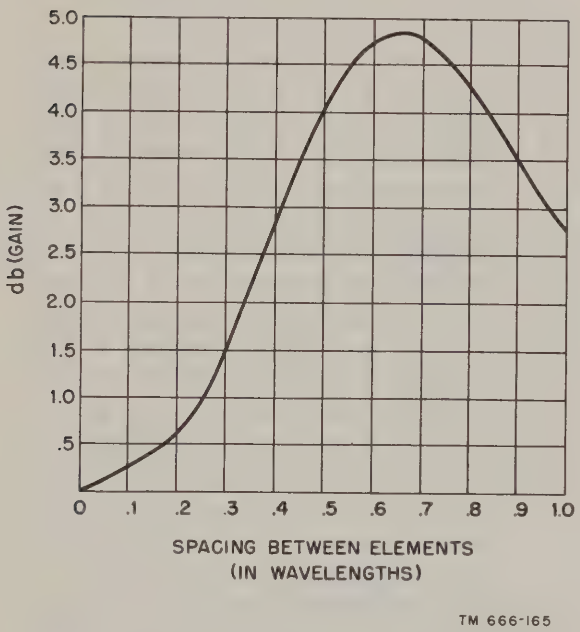

Figure 161. Spacing and gain, broadside elements.

(2) *Number of elements.* The increase in gain of a broadside array as more elements are added is marked as compared to the increase with a collinear system. Reduced radiation resistance resulting from the efficient coupling between dipoles accounts for most of this. However, certain practical factors limit the number of elements that may be used. The constructional problem increases with the number of elements, especially when they are polarized horizontally (upright ladder). The following chart shows the effect on gain by adding elements. With 3-quarter-wavelength spacing, the combined effects of optimum coupling and additional elements act to increase gain still further, and whenever more than two elements are used, minor lobes are developed regardless of the spacing. These lobes are greater than those developed by collinear arrays using the same number of elements.

Number of elements	Gain in db (λ/2 spacing)	Gain in db (3λ/4 spacing)
2	4. 0	4. 5
3	5. 0–5. 5	7. 0
4	6. 0–7. 0	8. 5
5	7. 0–8. 0	10. 0
6	8. 0–9. 0	11. 0

(3) *Radiation patterns.* A representative pattern for a broadside array with four elements is shown in figure 154. The pattern is taken in free space in the plane perpendicular to the elements. Since the elements are vertical, the characteristic broadside pattern is developed horizontally; the vertical pattern is that of the ordinary half-wave antenna. The characteristic pattern varies slightly from the illustrated free-space pattern when the elements are horizontal or stacked. This variation is a function of ground reflection. The resulting pattern can be developed by applying the reflection factor discussed in paragraph 58. For this purpose, the height above the earth of the center element (or the average height of the entire array) is considered to be the height from ground. The resultant low angle of radiation is a feature of this type of polarization.

c. Variations. When an antenna system consists of purely broadside, in-phase elements, there is little difference between one and another aside from the number of elements and the spacing, both of which have been discussed, and the means of feeding. The lazy H, Sterba curtain, and Bruce array all represent systems using collinear as well as broadside elements. There is also a popular four-element arrangement combining broadside with end-fire elements.

d. Phasing and Feeding.

(1) *Phasing.*

(*a*) One frequently used means of supplying currents in the same phase to broadside elements is shown in figure 162. In *A*, the feed line is connected directly to the center of the phasing section (vertical) between the dipoles. Consider that leg of the vertical section connected directly to the dipoles and its associated side of the feed line.

The two halves of this side of the section are parallel with respect to the feed point. Current traveling up this side of the feed line continues to move in exactly the same phase up one side of the section and down the other. Phase reversal in either portion of this line occurs at exactly the same distance away from the point of feed. Electrically, the driven elements are merely series extensions of these exactly phased portions of line. Therefore, current in them must be also in the same phase.

(*b*) Although the elements are represented as being exactly a half-wavelength apart, this need not be considered a rule when only two sections are involved. If the feed is introduced at the exact midpoint, correct phase is maintained regardless of the length of the phasing line. Advantage then may be taken of the larger optimum spacing, as indicated in the graph of figure 161. In *B* (fig. 162), where the array consists of more than two elements, adherence to half-wavelength spacing becomes necessary. The phasing of the two center dipoles is the same as in *A*. However, current traveling up the half-wavelength phasing section feeding the upper dipole undergoes a half-cycle of phase reversal. At the point where the section joins the top element, the current is 180° different from the desired phase. Connecting the element to the *opposite* side of the line, however, puts it exactly in the correct phase. The bottom element is driven in the same way. For the sake of clarity in showing the connections, the top and bottom dipoles have been made to appear slightly out of line with respect to the two in the center. In practice this is not necessary. The phasing lines may be transposed or dressed to accommodate the positioning of the dipoles. Here, spacings greater than a half-wavelength are not possible since the phasing lines must be exactly that long.

(*c*) Energy also can be introduced at the junction between the feed line (or matching device) and one of the elements (*A* of fig. 163). Current phase in the lower element, shown by the arrow, is determined by the feed. At the other end of the vertical phasing line (180° or 1 half-wavelength away), the upper dipole is connected to the opposite side of the line. Phase reversal in the line is canceled out, and the elements are kept in the same phase as desired. In *B*, phase is established for the upper element in the same way as for the upper dipole in *A*. The center dipole in *B* is connected just as is the lower element in *A*. The bottom element in *B* is connected and phased exactly as is the top dipole in the same array. Since they are exactly 1 wavelength apart, and exactly the same distance from the point of feed, they must be in the same phase. When three or any other odd number of broadside elements is used, this method of applying signal to the center of the array is desirable because it makes for better balance. If more elements are added to either side of the array, they are connected to alternating sides of the phasing line. In this way, every even dipole is connected to one side of the phasing line; every odd dipole is

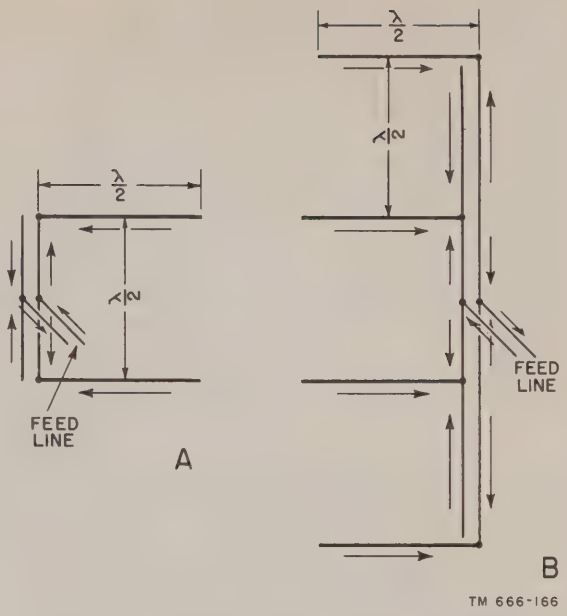

Figure 162. Phasing broadside arrays, first method.

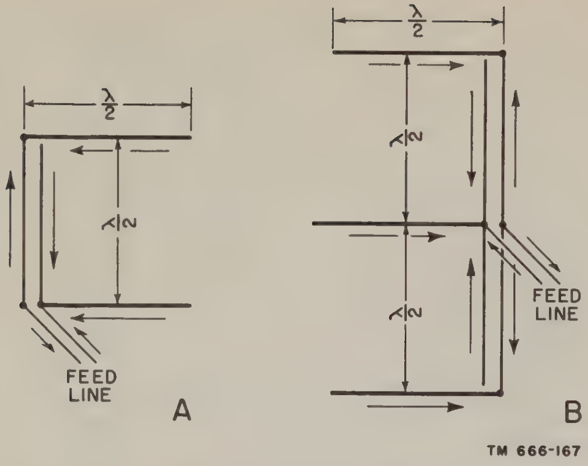

Figure 163. Phasing broadside arrays, second method.

connected to the other side. The same spacing restrictions are applied.

(*d*) The widely used method of feeding a half-wave dipole at its current loop (center of the dipole) also can be applied to the broadside array. In *A* of figure 164, the elements are a pair of dipoles, fed at their center points, and connected in parallel. At any spacing the elements are always in phase provided that energy is introduced at the center of the line between them. If additional elements are added to this basic arrangement, the array assumes the appearance shown in *C*, and the extreme dipoles must be connected to that side of the phasing section which is opposite to the side feeding the center elements. Another method for center-feeding the elements is shown in *B*. Energy is introduced to one of the extreme dipoles as though it were an ordinary, center-fed, half-wavelength section. All additional elements are joined at their centers to the continuous phasing line; the sides of the feeding line to which the respective halves of the elements connect are alternated throughout. The half-wavelength spacing restriction limits all of the arrays shown here just as it limits all of the multielement broadside arrays presented up to this point.

(*e*) When space permits, full advantage of the gain attainable with 0.6- to 0.7-wavelength spacing can be taken. Phasing sections a full wavelength long are inserted between one dipole and another. These connecting lengths are bent or dressed as shown in figure 165, or in some similar fashion. The space

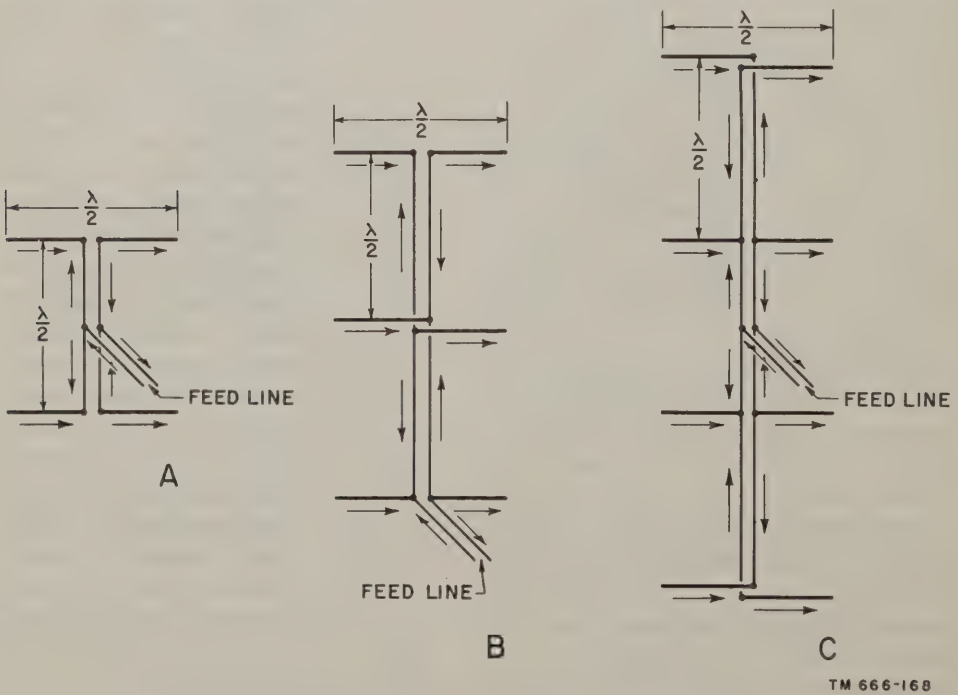

Figure 164. Phasing broadside elements, third method.

between elements in this example is 3 quarter-wavelengths. Current moving in any phasing section undergoes a full, 360° cycle of change so that it is fed to an element at the same phase point. With full-wave connecting lengths, all dipoles connect to the same side of the line. Any spacing up to 1 wavelength is made possible by this method. The feed line or matching device usually is connected where the phasing section joins an element. Feeding at the center section gives the best balance.

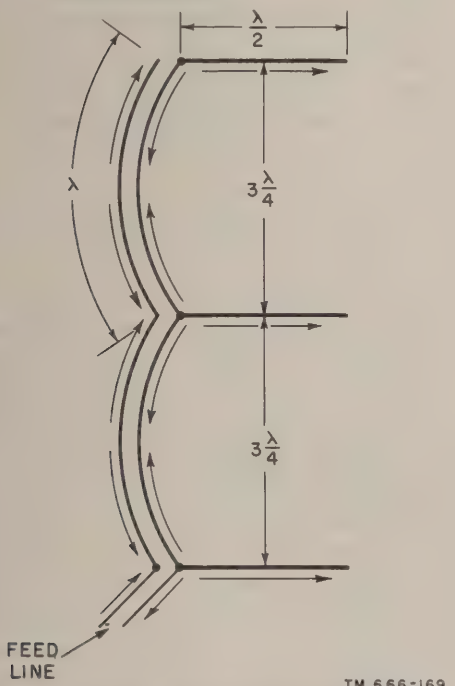

Figure 165. Phasing broadside elements, fourth method.

(2) *Feeding.* Broadside arrays may be fed by either resonant feeders or flat lines with matching devices. A two-element array phased by the resonant feeders presents an impedance of less than 100 ohms at the point of feed. Although the phasing line between the elements may be longer than a half-wavelength, it is only with an exact half-wavelength that the feed impedance is purely resistive. With other lengths, there is a reactive component that must be tuned out. When an array phased in this manner has four elements (*B* of fig. 162), the impedance at the point of input is about 250 ohms with open-wire phasing line. In any case where the transmission line is introduced at the end of one element, the impedance is approximately 1,000 ohms. When the transmission line is introduced as shown in *A* of figure 164, the input impedance is about 3,000 ohms. Where more elements are used with open-wire line as in *C*, the input impedance is about 1,500 ohms. Matching to the input of broadside arrays has to be worked out for individual cases.

103. End-fire Arrays

a. General Description.

(1) In appearance, an end-fire system does not look very different from a broadside array, the ladder-like appearance being characteristic of both. The currents in the elements, however, are 180° out of phase with each other. Because the plane in which the maximum radiation develops is in the plane of the elements, however, a vertically stacked arrangement is not likely to be operating as an end-fire array. Instead, the end-fire array is more likely to be constructed like a ladder lying on its side (elements vertical) or like one lying flat (elements horizontal). Moreover, the dipoles in an end-fire system are closer together (eighth-wavelength to quarter-wavelength spacing) than they are for broadside radiation.

(2) Closer spacing between elements permits compactness of construction. For this reason, an end-fire system is preferred to other types when high gain or sharp directivity is desired in a confined space. However, the close coupling creates certain disadvantages. Radiation resistance is extremely low, sometimes in the order of 10 ohms, making the possibility of antenna losses greater. Furthermore, this lower resistance is responsible for a higher Q, with the result that end-fire antennas are narrowly tuned affairs. This confines the array closely to a single frequency and introduces the danger of detuning with changes in climatic or atmospheric conditions.

(3) The major lobe or lobes occur along the axis of the array. The pattern is sharper

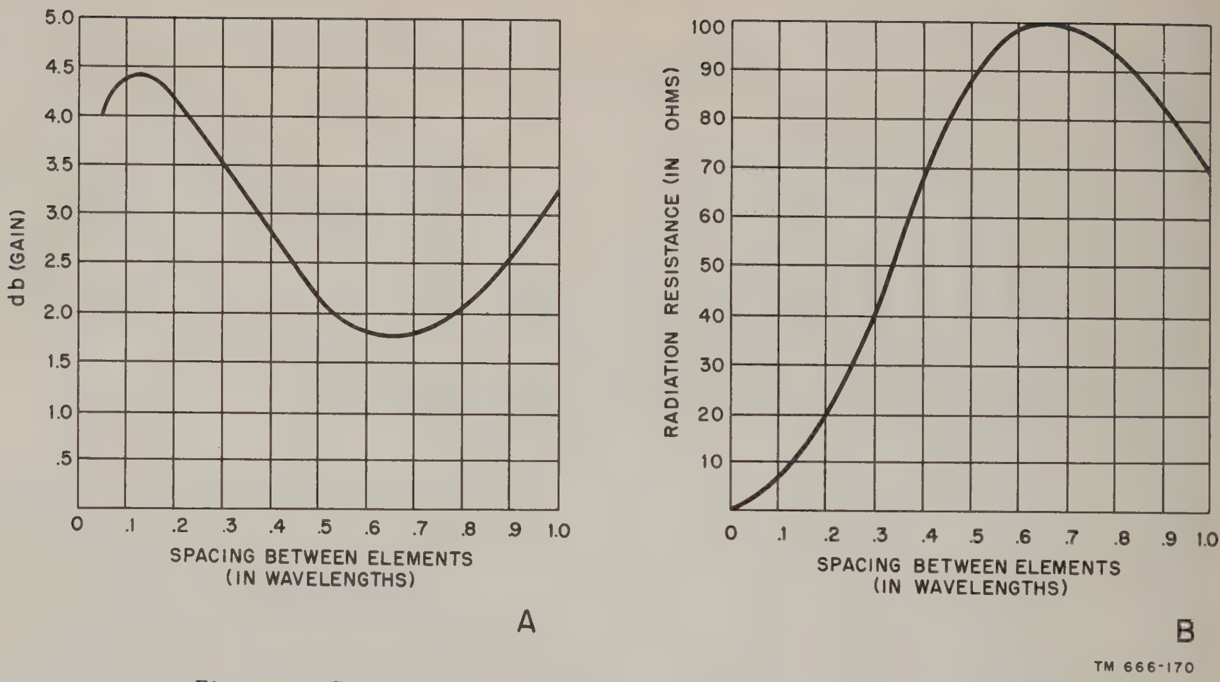

Figure 166. Spacing, gain, and radiation resistance with end-fire elements.

in the plane which is at right angles to the plane containing the elements. If the elements are not exact half-wavelength dipoles, operation is not affected materially. However, the required balance of phase relationships and critical feeding makes it important that the array be symmetrical. Folded dipoles are used frequently because the impedance at their terminals is higher. This is an effective way of reducing Q and avoiding excessive antenna losses. Another expedient to reduce losses is the use of tubular elements of wide diameter.

b. Gain and Directivity.

(1) The gain available from a pair of dipoles phased 180° apart at different spacings is graphed in *A* of figure 166. A comparison with a similar graph for the same pair of elements operated in phase, or as a broadside array (fig. 161) shows an inverse relationship between the two. This is caused by the inverse phase relationship. In *B*, the relationship between spacing and radiation resistance is shown.

(2) In end-fire arrays, directivity increases with the addition of more elements and with spacings approaching the optimum. The directive pattern for a two-element, bidirectional system is illustrated in figure 155, where *A* shows radiation along the array axis in a plane perpendicular to the dipoles, and *B* shows radiation along the array axis in the plane of the elements. These patterns were developed with 180° phase difference between the elements. Additional elements introduce small, minor lobes.

(3) With 90° phase difference in the energy fed to a pair of end-fire elements spaced approximately a quarter-wavelength apart, unidirectional radiation can be obtained. The pattern perpendicular to the plane of two elements is shown in *A* of figure 167. The pattern shown in *B*, taken in the same plane, is for a six-element array with 90° phasing between adjacent elements. Since both patterns show relative gain only, the increase in gain produced by the six-element array is not evident. End-fire arrays are the only ones wholly made up of driven elements that can be unidirectional.

c. Variations.

(1) End-fire elements are used frequently in combination with other types of elements to procure a particular kind of radiation pattern or to obtain extra gain. In figure 168, a four-element antenna, arrows

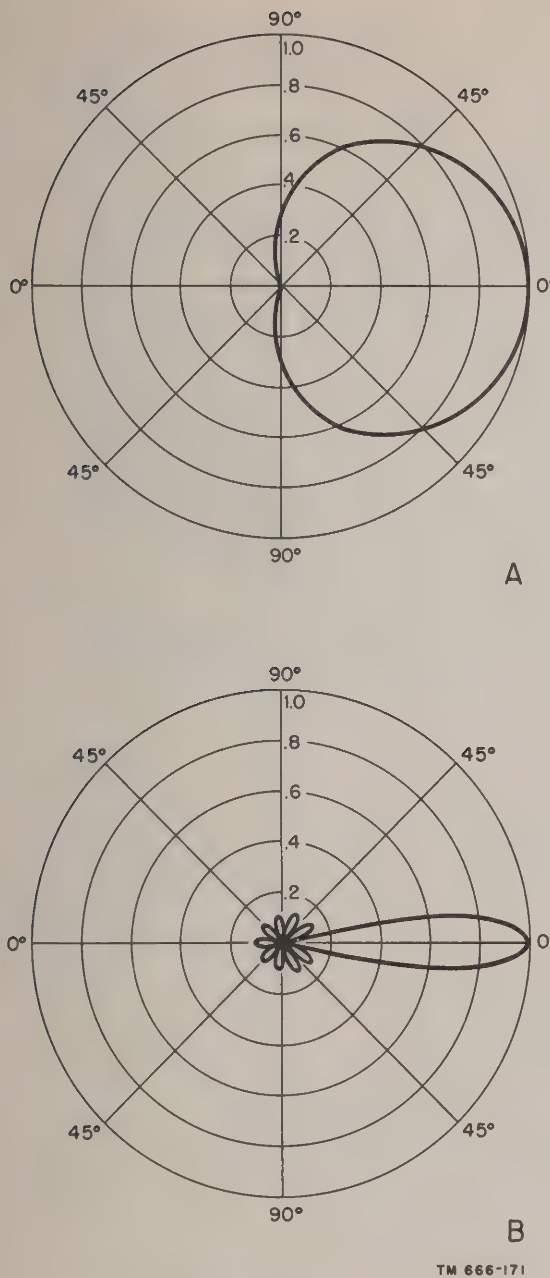

Figure 167. Unidirectional end-fire arrays.

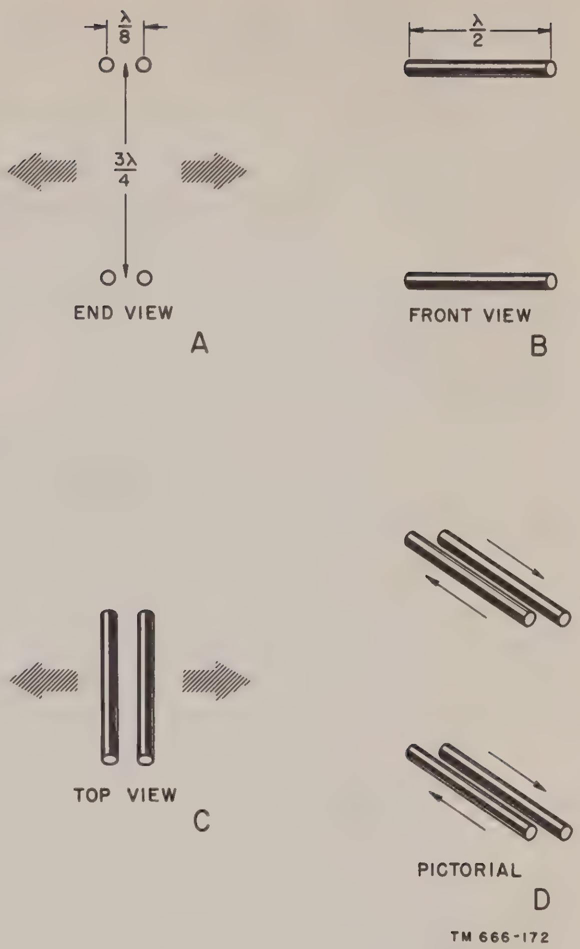

Figure 168. Combination end-fire and broadside elements.

indicate the directions in which bidirectional radiation develops. This antenna system can be regarded as a pair of two-element end-fire arrays, operating broadside to each other. The two top elements can be considered as one end-fire array, the bottom pair as another. The radiation pattern developed in the plane shown in *A* is similar to that shown in *A* of figure 155, except that the lobes are sharper and the entire pattern is rotated 90°. The pattern shown in *C* is like that of *B*, figure 155.

(2) The dipoles in figure 168 are fed at their centers, the main feed line branching into four legs, one feeding each element. The top and bottom elements on the right, in *A*, are in the same phase, or broadside. The two elements to the left are also in the same phase, but they are 180° out of phase with the elements on the right, as indicated by the arrows in *D*. The elements on the left are connected directly to the phasing section of the transmission line without transposition. Connections to the right-hand elements are transposed. Spacing between the left and right elements, shown as eighth-wavelength in the figure, actually can vary from that measurement up to a quarter-wavelength. Spacing between top and bottom elements, shown as 3 quarter-

wavelengths, can vary from 3 eighth-wavelengths to 3 quarter-wavelengths. Depending on spacing, gain for this combination array varies from about 6.5 db to about 9 db. The 9-db gain is obtained with the spacing indicated in *A*. Gain for any combination of spacings is obtained by adding the gain as read from the graph of figure 161 for the broadside spacing used to the reading from the graph of *A* of figure 166, for the end-fire spacing used.

d. Phasing and Feeding.

(1) *Phasing.*

(*a*) Principal methods of operating parallel elements 180° out of phase are shown in figure 169. The method shown in *A* is acceptable when spacing is no more than an eighth-wavelength. Here, either side of the single-leg phasing section is no greater than a sixteenth-wavelength, and very little radiation takes place from these short lengths. The methods used in *B* and *C* appear similar to broadside phasing techniques. Two fundamental differences, however, account for the 180° phase difference here as contrasted to to the in-phase relationship of broadside elements. The phasing sections and spacing are always considerably less than a half-wavelength, and the point of feed can be different. The arrows indicate the direction of current flow at a given instant. In *D*, a method for center-feeding many elements is shown. Whatever the spacing between elements, the lengths of the phasing lines between one element and the next must be exactly 1 half-wavelength to maintain the phase difference desired. Energy always must be applied at the junction of the phasing line with one of the elements.

(*b*) Phasing of unidirectional end-fire arrays requires a 90° difference and must be arranged in a different manner. Quarter-wavelengths of phasing line can be used to provide the quarter-cycle phase difference required. Another popular method for a two-element array involves two separate transmission lines, one for each element. The transmission lines are matched individually to the elements, and one of the lines is exactly a quarter-wavelength shorter or longer to produce the desired phase relationship. Both lines are of the same type and are fed simultaneously from a coupling circuit at the transmitter. The advantage of this method is that it provides control at the transmitter of the amount of current fed to each element. In this mode of operation, mutual coupling is not the same for both elements, with

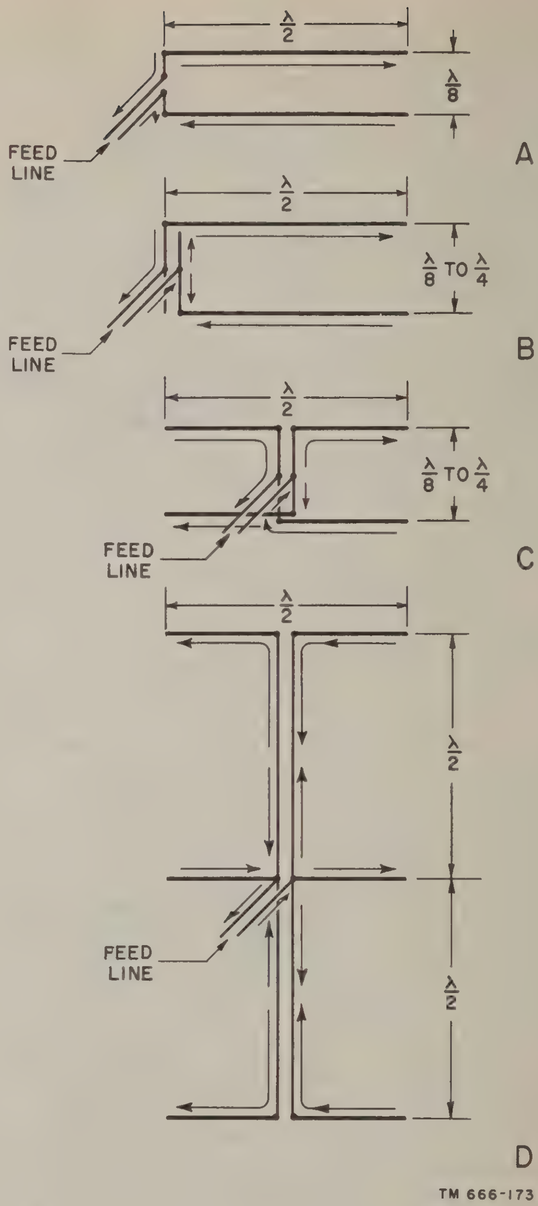

Figure 169. Phasing end-fire elements.

the result that each has a different radiation resistance.

(2) *Feeding.* With eighth-wavelength spacing of center-fed elements, radiation resistance falls as low as 8 ohms, and the standing-wave ratio becomes very high. The ratio can be in the order of 30 to 1 or higher, and this accounts for the critical tuning of such arrays. If the array is reasonably close to the transmitter, a tuned, open-wire line can be used, but when longer transmission lines are used, they should be matched carefully at the operating frequency to reduce the high standing wave ratio (SWR). Folded dipoles as end-fire elements are used to take advantage of the higher impedance at their terminals. The folded elements are fed and matched individually through quarter-wave stubs to increase impedance still further. It then is pòssible to reduce the SWR to no more than 2 to 1.

104. Other Driven Arrays

All of the driven arrays discussed so far have been basic collinear, broadside, and end-fire types. Some special combination driven arrays are discussed in the following paragraphs.

a. Extended Double-Zepp.

(1) *A* of figure 170, shows a two-element collinear array, with wide spacing, in which each element is longer than a half-wavelength, the optimum length usually being 0.64 wavelength.

(2) The greater than normal spacing between the half-wave sections at the ends of the wires carrying in-phase currents results in an increase in gain of slightly more than 1 db over the gain of the basic collinear array with two half-wave dipoles. Undesired radiation is small from the center of the array in which current flows in the opposite direction, because of the short sections of wire used (0.64 minus 0.5 is only 0.14 wavelength).

(3) The radiation from this array is bidirectional in a plane containing the two elements. A circular radiation pattern is produced in a plane that is at right angles to the elements.

b. Lazy-H Antenna Array.

(1) The lazy-H antenna array consists of two collinear arrays connected in parallel as shown in *B* of figure 170. Each collinear array, consisting of two half-wave elements, usually is spaced a half-wavelength from its neighbor. The current in each of the four half-wave elements is in phase, so that maximum radiation occurs at right angles to the plane of the array.

(2) The lazy-H array shown in *B* has a gain of about 6 db. Although smaller spacing between the two collinear portions can be used, a reduction in gain results. Larger spacing can be used also, which results in a slight increase in gain; however, the input impedance is no longer purely resistive as it would be with half-wave spacing.

(3) With the half-wave spacing, the input impedance is about 100 ohms (resistive). When a high input impedance is required

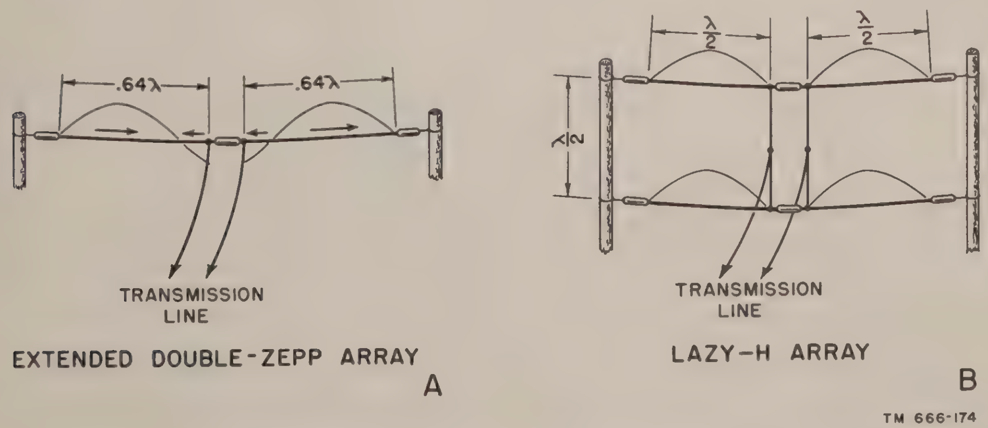

Figure 170. Extended double-Zepp and lazy-H arrays.

that is also resistive, the transmission line is connected directly at the lower center insulator, and the connecting line to the upper elements is transposed once. This is required to put the currents in the upper elements in phase with the currents in the lower elements. The input impedance then is in the vicinity of 2,000 ohms.

(4) The radiation pattern produced by this array is bidirectional in both horizontal and vertical planes. The beam width is not as broad as in the horizontal plane.

c. Sterba Curtain.

(1) The Sterba curtain, shown in *A* of figure 171, consists of two collinear arrays, usually made up of a large number of elements stacked one above the other. The spacing between the two collinear arrays is a half-wavelength.

(2) When the array is arranged as shown, only the horizontal elements produce useful radiation. The three twisted vertical sections of line do not radiate since one conductor of each pair carries current in one direction and the other conductor carries current in the opposite direction, and their fields, therefore, cancel. Also, the two single vertical half-wave conductors at either end of the array produce little radiation since the current flow in the upper half is in the opposite direction to that flowing in the lower half.

(3) Although the array shown in *A* consists of only three half-wave elements as the top section and a similar number as the bottom section (actually two half-wave elements in the center and two quarter-wave elements at the ends) it can be extended to include many more elements.

(4) The gain of the array is increased as it is lengthened to include more collinear elements. In the array shown, the equivalent of three collinear elements provides a gain of over 3 db. To this must be added the gain provided by operating the additional set of collinear elements beneath the first. This provides an additional gain of about 4 db, so that the total gain of the array is about 7 db.

(5) When the Sterba curtain is fed as illustrated, the impedance is about 600 ohms. This permits the use of a 600-ohm nonresonant two-wire line. Another common feeding point is at the exact center of the lower collinear array between the two half-wave sections. At this point, the input impedance of the array is about 1,000 ohms.

(6) A unique advantage of the Sterba curtain is that it provides a closed circuit for power-frequency alternating current or direct current. Such current sometimes is used to heat the elements to prevent ice formation.

d. Bruce Array.

(1) The Bruce array consists of a single wire folded as shown in *B* of figure 171. All vertical and horizontal lengths are a

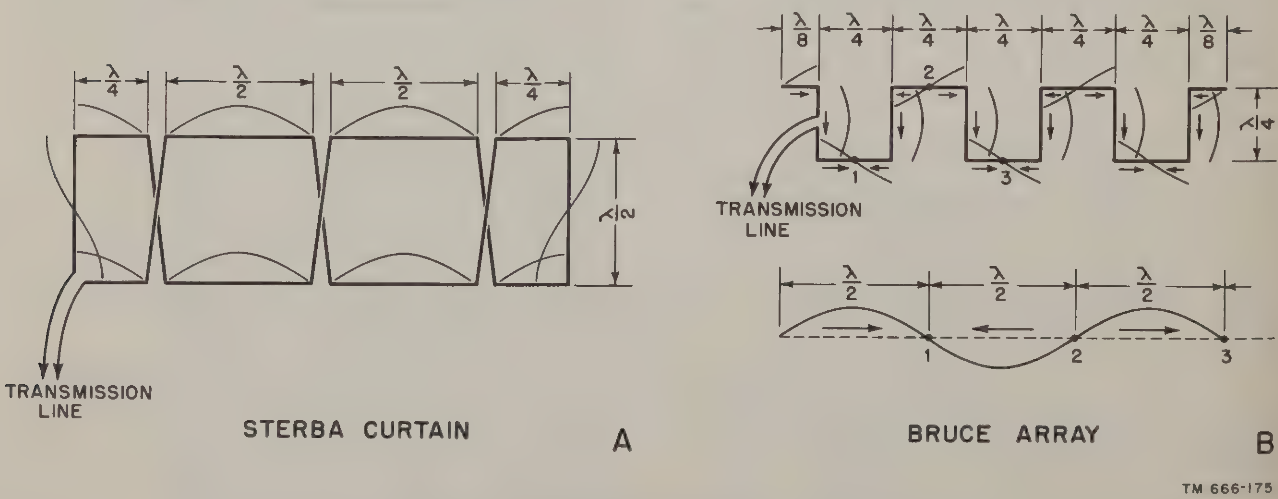

Figure 171. Sterba curtain and Bruce array.

quarter-wavelength with the exception of two at the ends of the array which are only 1 eighth-wavelength.

(2) The distance from the extreme left end of the array to point 1 represents a total distance of a half-wavelength (an eighth-wavelength plus a quarter-wavelength plus an eighth-wavelength). In this section of the array, current flows in the direction toward point 1 which is indicated by the current wave and the small arrows. In the next half-wave section, between points 1 and 2, a current reversal occurs. The current now flows from point 2 toward point 1. In the next half-wave section, between points 2 and 3, another current reversal occurs. The current now flows from point 2 to point 3. This portion of the array is unfolded in the dotted view so that the directions of current flow are made clear. Similar reversals occur throughout the length of the array.

(3) Because of the folding of the wire, the direction of current flow is the same (that is, down) in each of the six vertical quarter-wave sections comprising the antenna. On the other hand, half of the small amount of current that flows in the horizontal sections of the array flows in one direction and half flows in the opposite direction.

(4) As a result of the current distribution described above, the radiation produced by the vertical sections adds together, whereas the radiation produced by the horizontal sections is canceled out. Consequently, strong vertically polarized radiation results.

(5) The Bruce array functions are similar to those of a simple broadside array made up of six vertical elements. However, since the vertical elements are only a quarter-wavelength instead of the usual half-wavelength, considerably less gain is obtained than from an ordinary six-element broadside array. As a result, the array must be made at least several wavelengths in order to produce a worth-while gain. The Bruce array usually is fed at a current loop as in the illustration.

e. Flat-Top Array.

(1) The flat-top array (*A* of fig. 172) consists of two pairs of collinear elements, each a half-wavelength, mounted in a horizontal plane and separated from each other by 1 quarter- to 1 eighth-wavelength. Because of the transposed transmission line connecting these pairs, the direction of current flow in one pair of collinear elements is opposite to that in the other pair. This is indicated by the small arrows in *A*. The array is not only collinear but is also end-fire, as indicated by the two large arrows which represent the directions of maximum radiation. These directions are in the plane of the elements.

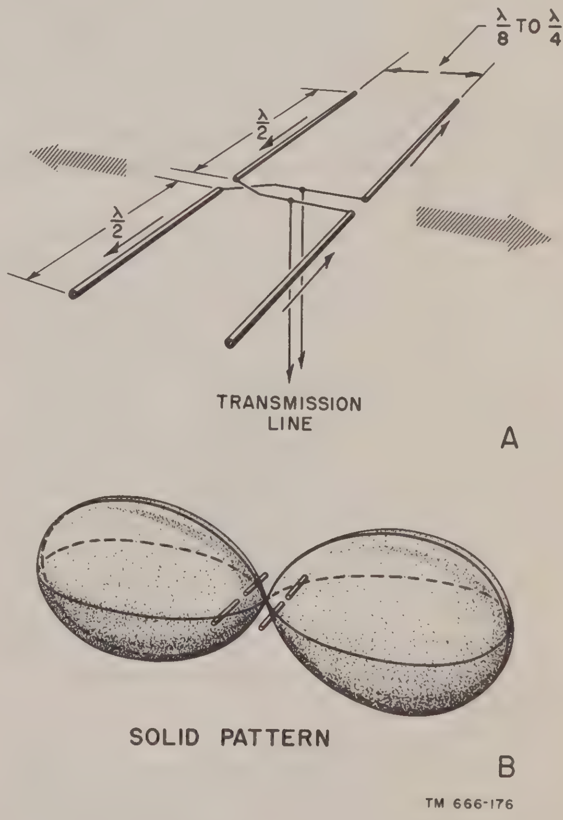

Figure 172. Flat-top array.

(2) The gain of the array shown is under 6 db when 1-quarter-wavelength spacing is used. With eighth-wave spacing, the gain increases slightly. The radiation pattern produced by this array is bidirectional in both horizontal and vertical planes. The beam width is narrower in the horizontal plane, as shown by the solid radiation pattern in *B*.

(3) The input impedance of the array is several thousand ohms. Therefore, resonant feeders generally are used. If a nonresonant line is to be used, a matching is required and the feeder must be connected properly on the matching section.

(4) The flat-top array can be constructed also of two half-wave elements instead of four. Here the array is not collinear, but is merely a close-spaced end-fire array. The gain is about 3 to 4 db and the input impedance is a low value.

Section III. PARASITIC ARRAYS

105. Parasitic Elements

a. General.

(1) Parasitic arrays represent another method of achieving high antenna gains. A parasitic array consists of one or more parasitic elements placed in parallel with each other and, in most cases, in the same line-of-sight level. The parasitic element is fed inductively by radiated energy coming from the driven element connected to the transmitter. It is in no way connected directly to the driven element.

(2) When the parasitic element is placed so that radiation is in the direction shown in *A* of figure 173, the element is a *director*. When the parasitic element is placed so that radiation is in the direction shown in *B*, the element is a *reflector*.

(3) The directivity pattern resulting from the action of parasitic elements depends on two factors. These are the *tuning*, determined by the length of the parasitic element and the *spacing* between the parasitic and driven elements. To a lesser degree, it also depends on the diameter of the parasitic element, since diameter has an effect on tuning.

b. Operation.

(1) When a parasitic element is placed a fraction of a wavelength away from the driven element and is of approximately resonant length, it will reradiate the radiated energy it intercepts. The parasitic element is effectively a tuned circuit coupled to the driven element much as the two windings of a transformer are coupled together. The radiated energy from the driven element causes a voltage to be developed in the parasitic element which, in turn, sets up a magnetic field. This magnetic field extends over to the driven element, which then has a voltage induced in it. The magnitude and phase of the induced voltage depend on the length of the parasitic element and the spacing between the elements. In actual practice, the length and spacing are arranged so

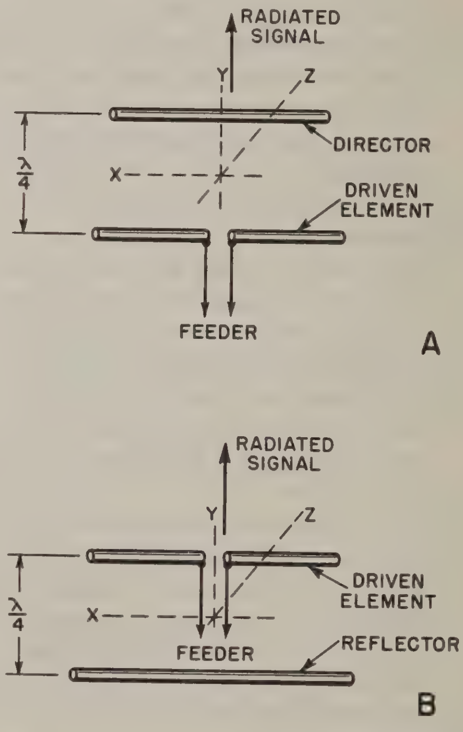

Figure 173. Position of the director and reflector with reference to the driven element.

that the phase and magnitude of the induced voltage cause a unidirectional, horizontal radiation pattern, with an increase in gain.

(2) In the parasitic array in *B* of figure 173, the reflector and driven elements are spaced a quarter-wavelength apart. The radiated signal coming from the driven element strikes the reflector after a quarter-cycle. The voltage developed in

the reflector is 180° out of phase with the driven element voltage. The magnetic field set up by the reflector induces a voltage in the driven element a quarter of a cycle later, since the spacing between the elements is a quarter-wavelength. The induced voltage is *in phase* with the driven element voltage, causing an increase in voltage in the direction of the radiated signal indicated. This forms the horizontal pattern in B of figure 174.

(3) Because the voltage induced in the parasitic element is 180° out of phase with the signal produced by the driven element, there is a substantial reduction in signal strength behind the reflector. In practice, since the magnitude of an induced voltage never quite equals that of the inducing voltage even in very closely coupled circuits, the energy in the minor lobe is not reduced to zero. In addition, very little radiation is produced in the direction at right angles to the plane of the elements.

(4) It can be shown also that when the parasitic element is a director, the horizontal and vertical radiation patterns will be as in *A*, figure 174.

(5) The radiation patterns shown have several advantages and disadvantages. The two main advantages of a parasitic array are increased *gain* and *unidirectivity*. There is a reduction of transmitted energy in all but the desired direction. This makes the parasitic array useful in antenna systems that can be rotated to a given direction. These are known as rotary arrays. Size for size, the gain and directivity of a parasitic array are greater than for a driven array. The disadvantages of these arrays are that their adjustment is critical and they do not operate over a wide frequency range.

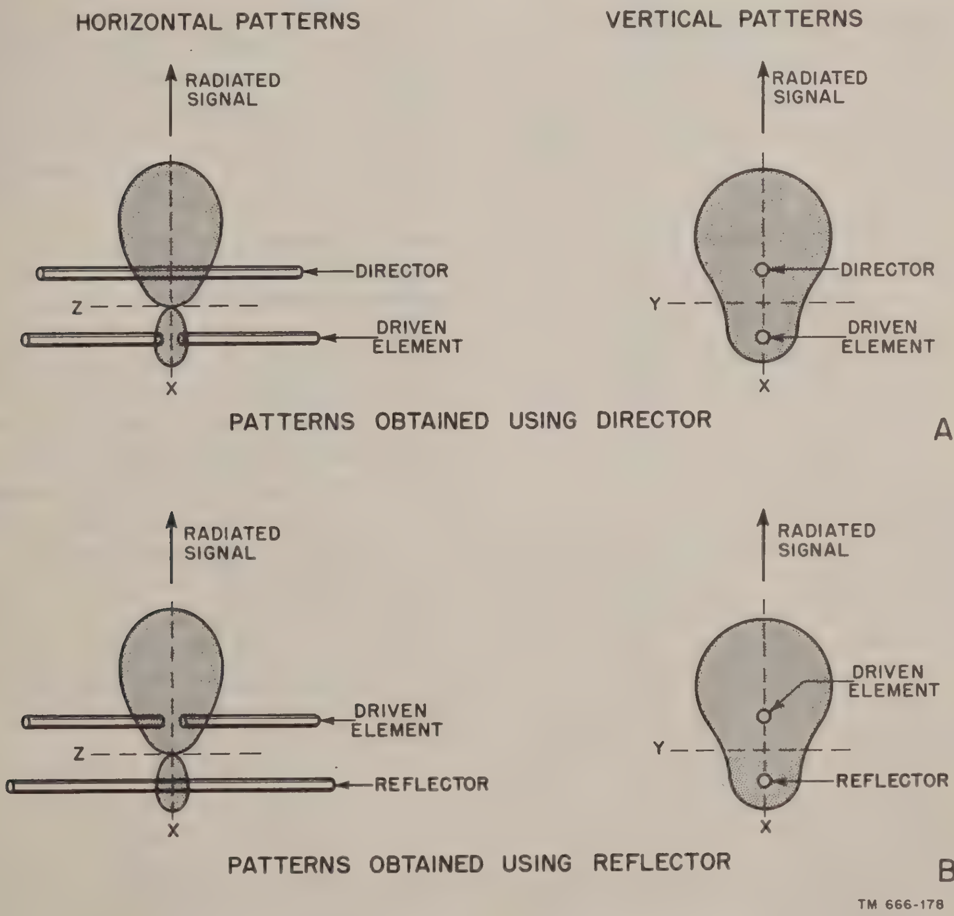

Figure 174. Patterns obtained using a parasitic element.

c. Relative Power Gain.

(1) Figure 175 is a graph of the relative power gain for various element spacings. The curve was plotted under the special condition that both elements are a half-wavelength long. The dotted curve shows the power gain when a reflector is used as the parasitic element. The zero reference line shows the power gain from the driven element alone.

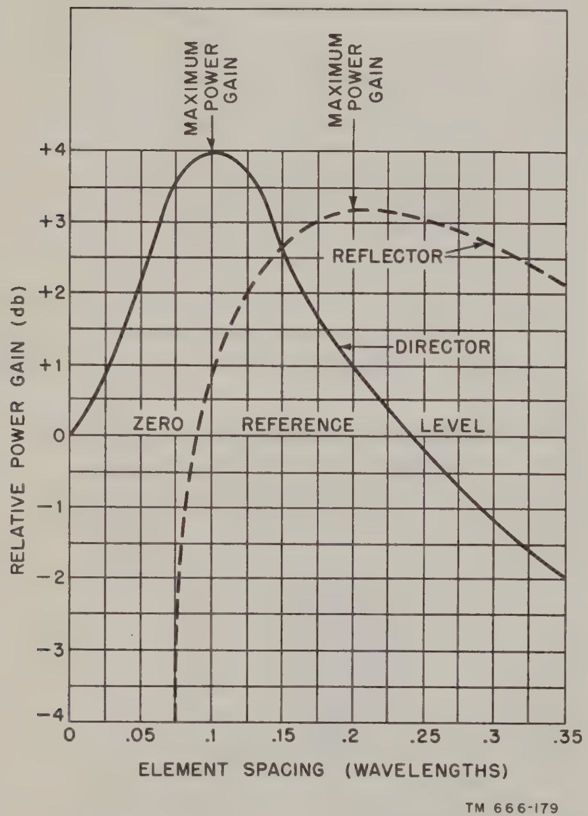

Figure 175. Relative gain for various spacings between elements.

(2) From the curves, it is seen that when the director is placed about 0.1 wavelength, or when the reflector is placed about 0.2 wavelength from the driven element there is power gain of 3 to 4 db. The curves also show that the director provides a greater power gain with less spacing between elements than does a reflector. However, the curves show that the gain does not change as rapidly when the spacing of a reflector is changed. Consequently, with only a single parasitic element the reflector is used, since its spacing is not so critical.

(3) The gain of a parasitic array depends on the length of the parasitic element as well as the spacing between elements. Figure 176 shows the gain when the length of the parasitic element is adjusted to obtain the most possible gain at any given spacing. There is, then, an increase in gain at any spacing between elements.

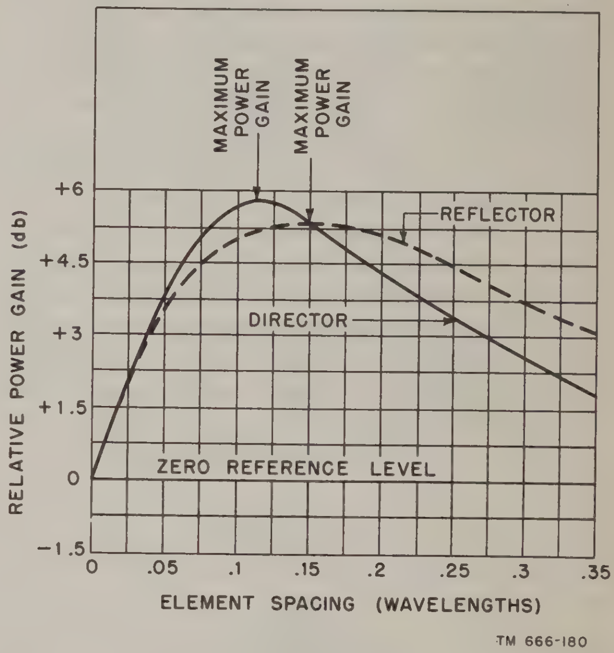

Figure 176. Relative gains of a parasitic array for various spacing between elements when the parasitic element is adjusted for greatest gain.

(4) In figure 176, it can be seen that the maximum gain with a director is almost 6 db at a spacing of slightly more than 0.1 wavelength. With a reflector, the maximum gain is 5.5 db at a spacing of 0.15 wavelength. The same power gain is obtained when the director is placed 0.15 wavelength from the driven element. Comparison of figures 175 and 176 indicates that more gain is obtained at any spacing when the length of the parasitic element is changed by tuning.

d. Front-to-Back Ratio.

(1) The front-to-back ratio of an array is the proportion of energy radiated in the principle direction of radiation (or reception) to the energy radiated (or received) in the opposite direction. It is desirable to have a high value of front-to-

back ratio because this means that the minimum amount of energy is radiated in the undesired direction. Since it is impossible to suppress all such radiation completely, an infinite ratio cannot be achieved, but rather high values can be attained in practice. It is usual to adjust the length and spacing of the parasitic element so that a maximum front-to-back ratio is obtained rather than maximum gain in the desired direction.

(2) In general, as the length of the parasitic element is *reduced* from a half-wavelength, it has a greater *capacitive* reactance. As the length is *increased* from a half-wavelength, it has a greater *inductive* reactance. The variation of the front-to-back ratio for different reactance values of parasitic elements is shown in figure 177. Here the *front* direction is assumed to be in a line *from* the parasitic element *to* the driven element. The spacing between elements in this particular case is held constant at 0.1 wavelength. At all negative reactance values (capacitive reactance) and at low values of positive reactance up to about +8 ohms, the parasitic element acts as a director with this value of spacing. When the inductive reactance increases beyond +8 ohms, as the parasitic element length is increased, this element acts as a reflector and the front-to-back ratio is 0.5. When the length of the parasitic element equals that of the driven element—that is, when both are tuned to the resonant frequency—the parasitic element is purely resistive and its reactance is zero. The parasitic element then behaves as a director and only half as much energy is radiated from the parasitic element toward the driven element as is radiated in the opposite direction. When the reactance of the parasitic element is +8 ohms, the front-to-back ratio is 1. This means that there is equal radiation in both directions and the parasitic element behaves neither as a director nor as a reflector.

(3) Tuning a parasitic element for a maximum front-to-back ratio does not mean, necessarily, that the array provides a maximum power gain. With the director that is tuned for maximum power gain (6 db, fig. 176), the resonant length of the director can be changed by experimenting so that the front-to-back ratio is increased 10 times with a reduction in the power gain of less than 1 db.

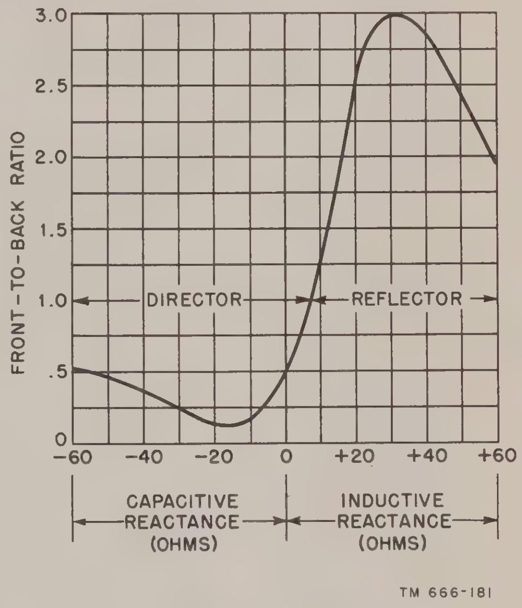

Figure 177. The front-to-back ratio of a parasitic array with varying reactance of the parasitic element.

e. Radiation Resistance.

(1) The elements of a parasitic array must be spaced a fraction of a wavelength from each other to obtain high power gain and high front-to-back ratio. When this is done, however, the radiation resistance of the driven element is altered considerably. The closer the spacing between elements, the smaller the radiation resistance becomes; the greater the spacing, the larger the radiation resistance (approaching the free-space value). The resulting low values of radiation resistance in parasitic arrays have several effects, not only limiting the number and type of feeding systems that can be used, but also reducing the radiation efficiency of the array.

(2) The reason for the low values of radiation resistance in parasitic arrays is explained as follows: Since both elements are placed extremely close to one another, the voltage induced back in the driven

element as a result of the parasitic element is almost equal in magnitude to the original driven element voltage. Since these voltages are out of phase with each other, a cancelation effect exists at the driven element. This reduces the voltage at the driven element which, therefore, causes a reduction in its feed-point resistance with the same input power. The closer the elements, the greater is the cancelation effect, and the lower is the radiation resistance.

(3) The manner in which radiation resistance varies with different element spacings is shown in figure 178, where both driven and parasitic elements are resonant. Note from the curve that the radiation resistance increases as either the reflector or the director is moved farther away from the driven element. The lowest radiation resistance is slightly greater than about 8 ohms when the elements are very close together. For spacings as great as 0.3 wavelength, when a reflector is used, the radiation resistance goes as high as 66 ohms. When a director is used at this spacing, the resistance is about 56 ohms. This indicates that larger radiation resistance values can be acquired when using the parasitic element as a reflector.

(4) The maximum power gain with a reflector and a director occurs at element spacing of 0.2 and 0.1 wavelength, and the parasitic elements are the same length as the driven element. At these spacings, the radiation resistance values with the reflector and director are 36 ohms and 14 ohms, respectively. These values are very small compared with a radiation resistance of about 73 ohms for the driven element alone. So, although the power gain of a parasitic array is large, the radiation efficiency may be low. In the selection of the type of array that is to be used for an antenna system, it first must be determined whether maximum power gain or radiation efficiency is desired. For maximum radiation efficiency, the driven array is used, and for maximum power gain the parasitic array is used.

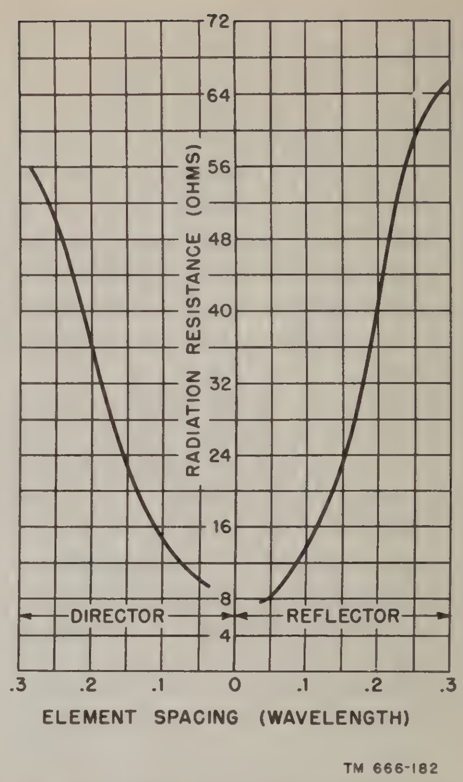

Figure 178. Curve showing radiation resistance at the driven element for various spacings of driven and parasitic elements.

f. Radiation Patterns.

(1) The radiation patterns of a parasitic array depend on the spacing between elements and the length of the parasitic element. The reactance reflected by the parasitic element is a direct function of its length. When the parasitic element is longer than a half-wavelength, it behaves as an inductive reactance. The induced parasitic voltage leads the induced current, and the parasitic phase angle is *positive*. When the parasitic element is shorter than a half-wavelength, it behaves as a capacitive reactance. The induced parasitic voltage lags the induced current, and the parasitic phase angle is *negative*. These angles are indicated in figure 179, which shows several radiation patterns in the horizontal (xz) plane for various element spacings and parasitic phase angles. The power input to the driven element is the same in each case. The radiation resistance is shown above each pattern.

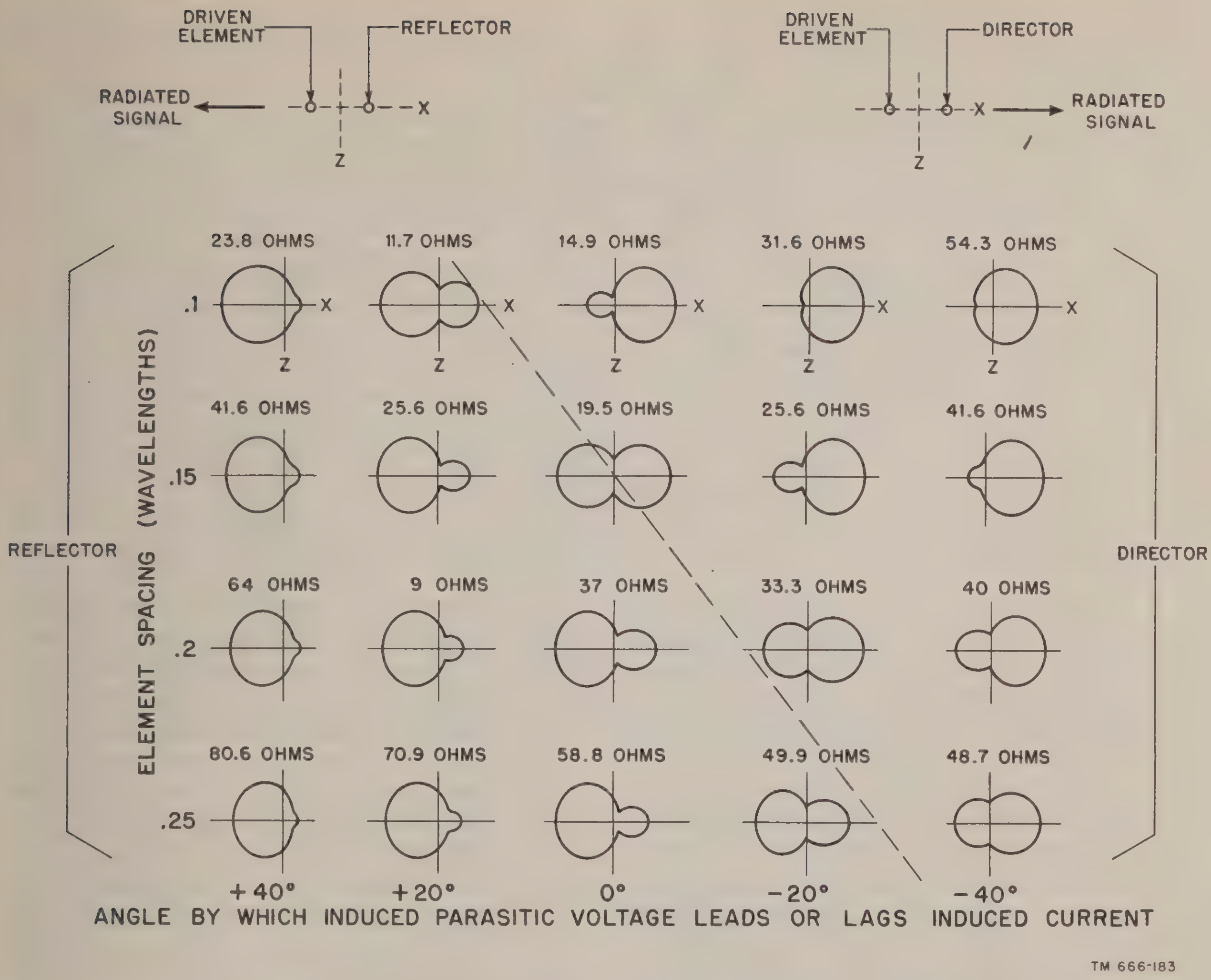

Figure 179. Radiation patterns of a parasitic array for various element spacings and phase angles.

(2) At 0.15-wavelength element spacing and a phase angle of 0° (with parasitic element resonant), the radiation pattern is bidirectional. When the spacing is 0.15 wavelength and the angle is +20°, the parasitic element acts as a reflector, but at a spacing of 0.15 wavelength and an angle of −20°, the parasitic element acts as a director. The diagonal dotted line indicates the dividing line between reflector and director action. If the spacing between elements is other than 0.15 wavelength, making the length of a parasitic element shorter than a half-wavelength (resonant length) does not necessarily make it behave as a director, as shown by the pattern obtained at a spacing of 0.25 wavelength and a phase angle of −20°. Since the angle is negative, the parasitic element is shorter than its resonant length which ordinarily makes it appear as a director. However, the radiation pattern indicates that it actually behaves as a reflector.

g. Frequency Response.

(1) As mentioned previously, the parasitic array has a comparatively narrow frequency range. Well outside this range, the effect of the parasitic element is small and the driven element alone controls the over-all characteristics. Figure 180 shows the frequency response of a driven element alone contrasted with a parasitic array using a director and a reflector. The reflector curve is that obtained when the length of the reflector produces maximum power gain with a spacing between elements of 0.2 wavelength. The di-

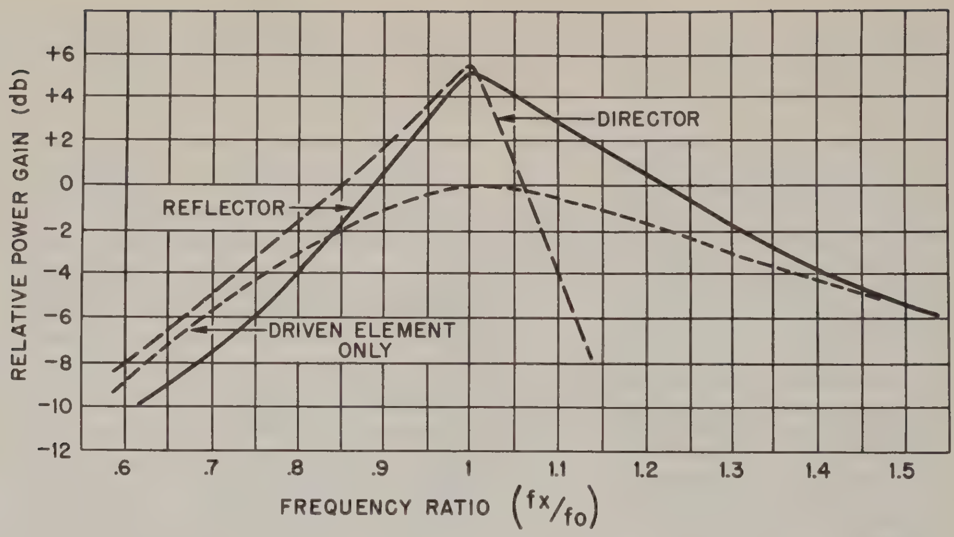

Figure 180. Frequency coverage of a driven element contrasted with an array using a director and a reflector.

rector curve is that obtained when the physical length of the director produces maximum power gain, with the spacing between elements 0.1 wavelength. The diameter of the elements is about 0.006 wavelength. Ratio f_x/f_o is the frequency applied to the array compared with the resonant frequency of the driven element.

(2) In the curve showing the frequency range of the driven element alone, a maximum power gain of 0 db (reference gain) is obtained when f_x/f_o equals 1; that is, when the frequency of the radiated signal equals the resonant frequency of the driven element. As the frequency of the applied signal decreases, the f_x/f_o ratio decreases, and the relative power gain decreases. As the frequency of the applied signal increases, the f_x/f_o ratio increases, and the relative power gain decreases. In other words, a decrease or an increase in the applied frequency causes a decrease in the power gain. This curve tapers off gradually as the frequency is changed, which indicates that the frequency response of the driven element alone is fairly broad.

(3) Consider the reflector curve. Maximum power gain (+5 db) results when the applied frequency equals the resonant frequency of the driven element. However, the power gain decreases sharply as the applied frequency is increased or decreased. This indicates the narrow frequency response. When the applied frequency is increased by only 10 percent (f_x/f_o=1.1), the power gain drops 2 db—that is, from +5 to +3 db. When the applied frequency is decreased 10 percent (f_x/f_o=0.9), the power gain drops 4.5 db, from +5 to +0.5 db. At the f_x/f_o ratios of 0.88 and 1.23, there is a no-power gain compared with that of the driven element acting alone. The points where the driven element curve and the reflector curve intersect (f_x/f_o=0.84 and 1.45) indicate that the same power gain results at this frequency ratio regardless of whether the reflector is used in the array. At all ratios lower than f_x/f_o=0.84, a greater power gain is obtained when using the driven element alone.

(4) In the director curve, a similar action results. When f_x/f_o ratio equals 1, maximum power gained is obtained. As the frequency ratio increases or decreases, the curve drops off rapidly, showing a sharp decrease in power gain. The director curve tapers off much more rapidly for ratios greater than 1 compared to the reflector curve. With ratios less than 1, the curve tapers off slightly less rapidly than the reflector curve. Therefore, the frequency response of the array with a director is very much narrower than that of the array with a reflector.

106. Multiparasitic Arrays

a. A multiparasitic array is one which contains two or more parasitic elements with the driven element. If the array contains two parasitic elements (a driven element, a reflector, and a director), it usually is known as a *three-element beam*. If three parasitic elements are used, the array then is known as a *four-element beam*, and so on. Generally speaking, if more parasitic elements are added to a three-element beam, each added element is a director. For example, a *five-element beam* contains one driven element, one reflector, and three directors. Most parasitic arrays do not use a greater number of elements than this.

b. The parasitic elements of a multiparasitic array usually are positioned as shown in figure 181. *A* shows a three-element beam, *B* a four-element beam, and *C* a five-element beam. Although the spacing between elements is typical of those normally encountered, many variations may be found. Frequently, the best spacings are found experimentally. In a three-element beam, the director usually is made slightly shorter and the reflector is made slightly longer than the driven element. The length of the second director in a four-element beam usually is shorter than the one nearest the driven element, and each additional director is made shorter than the previous one. A folded dipole can be used as the driven element to obtain greater values of radiation resistance.

c. The reason for using a multiparasitic array is to obtain greater power gain and unidirectivity. In addition, a larger front-to-back ratio can be obtained with proper parasitic tuning. In general, the more parasitic elements used, the greater is the power gain. However, a greater number of such elements causes the array to have a narrower frequency response characteristic and become critical to adjust. The gain of a parasitic array does *not* increase directly with the number of elements used. For example, the three-element beam shown in the figure has a relative power gain of 5 db. Adding another director results in only a 2-db increase, or a total gain of about 7 db. If another director is added to the array, an increase of less than 1 db results, making the total gain less than 8 db. It is seen that the director closest to the driven element has the greatest effect on the gain; the one farthest away has the least effect. Consequently, as more directors are added, the effect on radiation resistance becomes smaller and smaller. Regardless of how many directors are added to the array, only a single reflector is used, because very little radiation goes behind this reflector.

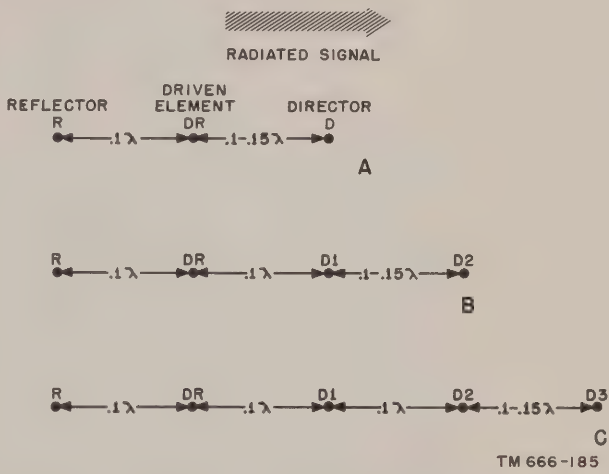

Figure 181. Examples of spacing between elements of multiparasitic arrays.

d. When there are two or more parasitic elements in a multiparasitic array, it sometimes is referred to as a *yagi* array. A typical yagi array used for receiving and transmitting radio energy is shown in figure 182. This antenna, used by the military services, operates at frequencies from 12 to 50 mc and consists of two separate yagi arrays mounted on one frame (one high-frequency and one low-frequency antenna array.) The various elements are indicated in the figure. The high-frequency array consists of one reflector, one driven element and two directors; the low-frequency array has the same arrangement with one less director. The lengths of the elements in the high-frequency array are shorter than those in the low-frequency array. The physical lengths of the elements in the individual arrays are equal, but the electrical lengths can be varied by means of the tuning stubs at the center of the elements. The array can be rotated in any desired direction by a remotely controlled, electrically driven, antenna rotator. Some of the characteristics of this array are given in the chart below.

Range	Number of elements	Power gain	Front-to back ratio	Feeding of driven element
l-f	3	7 db	25 db	52- to 600-ohm transmission line fed directly to T-matching section of driven element.
h-f	4	9 db	30 db	52- to 600-ohm transmission line using inductive coupling to driven element.

(2) A simple field intensity meter or high-input impedance vacuum-tube voltmeter may be used as the adjustment indicator.

(3) No transmitter adjustments are necessary.

(4) The r-f voltage induced in the antenna elements is of such low magnitude that the elements, including stubs and *T*-match sections, may be touched and handled without endangering personnel with r-f burns.

(5) Fewer personnel are needed to make the adjustments.

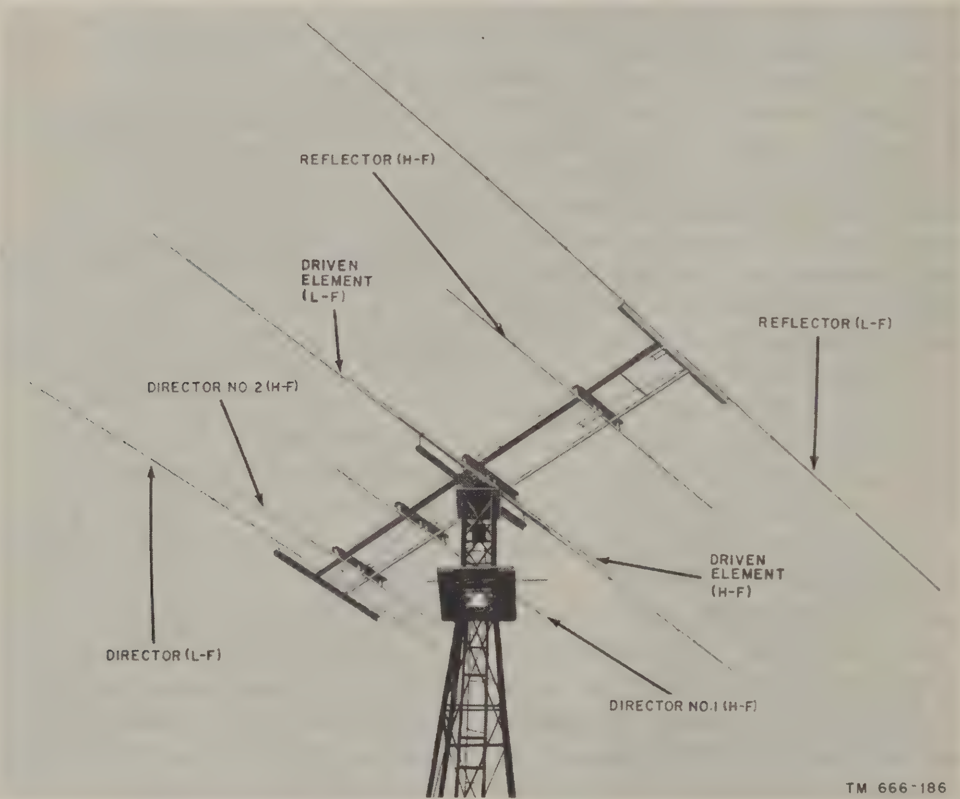

Figure 182. A typical parasitic array used for receiving and transmitting.

107. Tuning, Adjusting, and Feeding

a. There are many methods of tuning and adjusting parasitic arrays. Regardless of which method is used, and whether it is to be used for transmitting or receiving, the parasitic array usually is set up as a *receiving* array when it is adjusted. Some of the reasons for doing this are given below.

(1) The parasitic array is immersed in a radiated field of constant intensity which, in turn, gives truer indications.

b. In many instances, the elements of a parasitic array contain telescopic sections which permit the physical length of the elements to be lengthened or shortened. It is customary first to adjust physical lengths approximately before attempting final adjustments. The following formulas can be used:

$$\text{length (in feet) of driven element} = \frac{468}{f}$$

$$\text{length (in feet) of reflector} = \frac{492}{f}$$

$$\text{length (in feet) of director} = \frac{450}{f}$$

where f is in megacycles in all cases. As an example, if a three-element beam is to operate at a frequency of 100 mc, the approximate physical lengths of its driven element, reflector, and director, respectively, are 468/100 or 4.68 feet, 492/100 or 4.9 feet, and 450/100 or 4.5 feet.

c. The method by which the driven element of a parasitic array is fed determines the method used in adjusting it.

d. A typical arrangement used for tuning and adjusting the elements of a four-element beam is shown in figure 183. A half-wave exciting dipole is fed by a low-power transmitter. This dipole radiates energy to the parasitic array. The power output of the transmitter must be held constant during the procedure. The spacing between the parasitic array and the exciting dipole is 2 or more wavelengths. The driven element of the parasitic array is connected through a 600-ohm balanced line to a field intensity meter or a high-impedance vacuum-tube voltmeter by means of a *T*-matching section. These meters need not be calibrated, since only relative values of r-f voltage are required to be measured. The lengths of all of the elements are adjusted electrically (tuned) by the adjustable tuning stubs.

e. The method and points to remember in tuning and adjusting the array are as follows:

(1) The height of the array should be a reasonable distance from the ground so that the element adjustments may be made conveniently. Very large arrays should be placed as much as 10 to 12 feet off the ground. In this case, the adjustments can be reached by a ladder.

(2) The height of the exciting array must be the same as the parasitic array so that a constant large amount of radiated energy may be received by the array.

(3) The low-power transmitter must be as close to the exciting dipole as possible. This means that the transmission line connecting the two must be as short as possible. In this way, it is less likely that the parasitic array will pick up radiation from the transmission line or from the transmitter directly.

(4) The spacing between the exciting dipole and parasitic array must be 2 or more wavelengths for the reason given above. If the distance is made too great, on the other hand, the parasitic array might not pick up sufficient energy to actuate the meter.

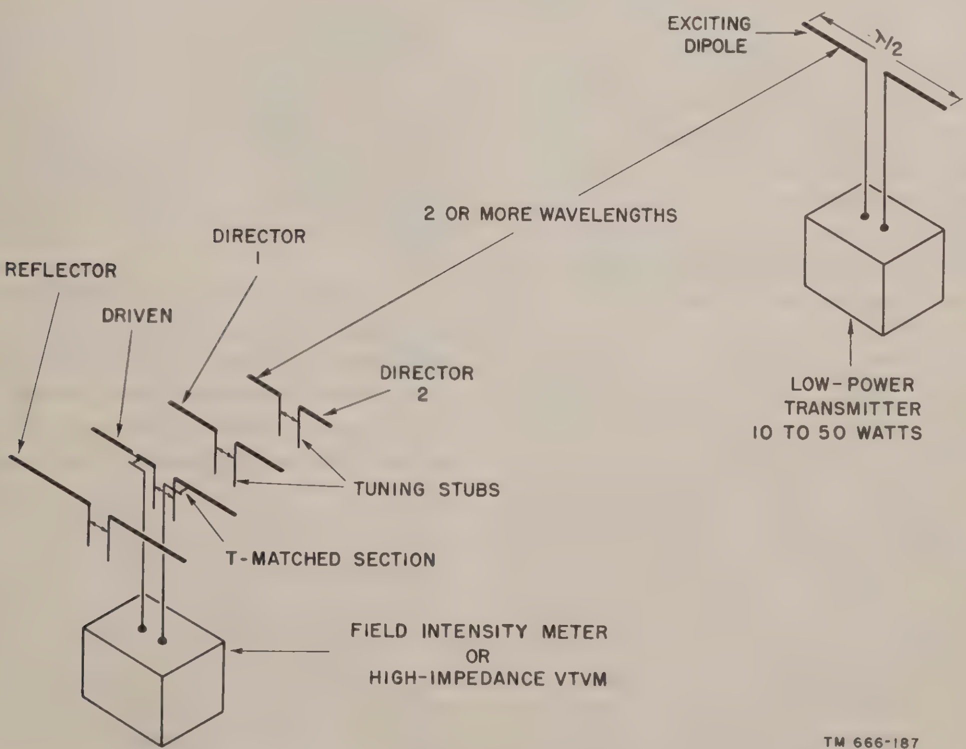

Figure 183. Typical arrangement for tuning and adjusting a four-element beam.

(5) The *T*-matching section and the tuning stub of the driven element are adjusted for a maximum meter reading, and the stub of the director element closest to the driven element is adjusted for maximum meter reading. The stub of director No. 2 then is adjusted for a maximum reading.

(6) The antenna is rotated 180° so that the reflector element is closest to the exciting dipole. The stub of the reflector then is adjusted for a *minimum* meter reading, to insure that the reflector produces a maximum attenuation in the unwanted direction of radiation.

Section IV. SUMMARY AND REVIEW QUESTIONS

108. Summary

a. An array is a combination of half-wave elements operating together as a single antenna. Arrays provide more gain and greater directivity than single-element antennas.

b. In a driven array, all elements derive their power directly from the source. In a parasitic array, one or more (parasitic) elements derive power by coupling from another element or other elements.

c. Arrays can be bidirectional or unidirectional. A bidirectional array radiates equally in two opposing directions along a line of maximum radiation. A unidirectional array radiates well in a single direction.

d. The elements in a collinear array lie in the same straight line, and maximum radiation occurs at right angles to this line. The currents in all elements must be in the same phase.

e. The elements in a broadside array are all parallel and in the same plane. Maximum radiation develops in the plane at right angles to the plane of the elements. The currents in all elements are in the same phase.

f. The elements in an end-fire array also are parallel to each other and in the same plane, but maximum radiation occurs along the axis of the array. Currents in adjacent elements are never in the same phase. A 180° phase difference from element to element is most common and produces bidirectional radiation. A 90° phase difference results in a unidirectional pattern.

g. At points distant from the array, radiation is either stronger or weaker than from a single element, depending on the direction of the point with respect to the array. At some angles, combined radiation from the various elements results in reinforcement; at other angles, combined radiation results in cancelation. The degree of cancelation of reinforcement is a function of the relative phase of radiation from different elements combining in space.

h. Matching stubs or sections are used between elements to maintain current in the desired phase.

i. The impedence of an antenna element acting alone (selfimpedance) differs from its impedance when it is acting with other elements in an array. Mutual impedance accounts for the difference between these two.

j. When collinear elements are a half-wavelength, the length of the stub between them is a quarter-wavelength. When the elements are longer, the length of the stubs is reduced correspondingly. In any one array, all elements must be of the same length.

k. The gain of a collinear array depends on the number of elements used and the space between elements. Gain is greatest when this spacing is 0.4 to 0.5 wavelength. Gain also increases as the number of elements is increased.

l. Collinear antennas can be fed adequately by resonant lines. Feed usually is introduced at a point between the ends of two elements, where the impedance is in the order of 1,500 ohms. Feed also can be introduced at the center of one of the elements. For best balance, the transmission line is introduced at the center of the array.

m. Optimum gain is obtained from broadside arrays when the elements are spaced 0.65 wavelength apart. However, half-wave spacing, which provides good gain, simplifies phasing.

n. When a broadside array is stacked vertically, height requirements usually limit the number of elements used; when the dipoles are vertical, more than six elements rarely are used.

o. There are two principal means for bringing currents into broadside elements in the same phase. When the phasing line between dipoles is a half-wavelength, alternate elements are connected to opposite sides of the line. When the lengths are 1 wavelength, all elements are connected to similar sides of the line.

p. The optimum spacing between end-fire elements is an eight-wavelength.

q. The radiation resistance of end-fire arrays is very low.

r. Radiation resistance can be increased and feeding can be simplified by the use of folded dipoles and impedance step-up matching devices.

s. The extended double-Zepp antenna consists of a two-element collinear array in which the length of each element is somewhat longer than a half-wavelength.

t. The lazy-H antenna array consists of two collinear arrays connected in parallel and spaced a half-wavelength apart in the vertical plane.

u. The Sterba curtain consists of two collinear arrays, usually made up of a large number of elements, stacked one above the other at a spacing of a half-wavelength. The form of the array is such that a closed loop is formed by the conductors making up the array.

v. The Bruce array consists of a single wire folded into horizontal and vertical quarter-wave sections.

w. The flat-top array consists of two pairs of collinear elements, mounted in a horizontal plane and separated from each other by a small spacing (approximately an eighth- to a quarter-wavelength).

x. A parasitic array consists of one or more parasitic elements along with a driven element.

y. The director usually is made shorter and the reflector usually is made longer than the driven element to obtain a large power gain.

z. The amount of power gain and directivity of a parasitic array depends on the lengths of the parasitic elements and the spacing between elements.

aa. When the length of a parasitic element equals that of the driven element, a maximum power gain exists when the parasitic element is used as a director and is placed 0.1 wavelength from the driven element, or when it is used as a reflector and placed 0.2 wavelength from the driven element.

ab. When the length of a parasitic element is tuned for a maximum power gain at any given spacing between elements, it is found that maximum power gain for the director results at 0.1 wavelength spacing and for the reflector at 0.15 wavelength spacing.

ac. Some power gain must be sacrificed when a parasitic array is tuned to obtain a maximum front-to-back ratio.

ad. The radiation resistance of the driven element of a parasitic array is very much less than that of a driven array. This, in turn, reduces its radiation efficiency.

ae. The parasitic array has a comparatively narrow frequency range of optimum operation.

af. The frequency response of a parasitic array using a reflector is wider than the frequency response of an array using a director.

ag. Multiparasitic arrays are used to obtain greater power gain, directivity, and front-to-back ratios.

ah. When tuning and adjusting a parasitic array, it usually is set up as a receiving array.

ai. The approximate physical lengths of the elements of a parasitic array are as follows:

$$\text{length (driven element)} = \frac{468}{f}$$

$$\text{length (reflector)} = \frac{492}{f}$$

$$\text{length (director)} = \frac{450}{f}$$

where the length is in feet and f is in mc.

aj. When tuning a parasitic array, the elements are tuned in this order: the driven element, the director nearest the driven element, all other directors, and the reflector.

109. Review Questions

a. What is an array? A driven array? A parasitic array?

b. What are the advantages and disadvantages of arrays as compared with other antennas?

c. Describe a collinear array, with special attention to the following features: arrangement and number of elements, phase relationship, radiation pattern.

d. In what ways is a broadside array likely to differ from an end-fire array in appearance?

e. Explain the difference in operation between broadside and end-fire arrays. Compare them as to the following features: plane of directivity, radiation resistance, phase relationship, spacing, feeding.

f. What is mutual impedance?

g. What is the gain of three collinear elements with negligible spacing between the elements?

h. What is the gain of two collinear elements with 3-quarter-wavelength center-to-center spacing?

i. What is the radiation resistance of two collinear elements with 0.35-wavelength spacing between their adjacent ends?

j. What is the best point in a collinear array at which to introduce the feed? Why?

k. For purposes of calculating reflection effects, what is considered to be the height of a broadside array above ground?

l. Two parallel elements, half a wave apart, must be phased for broadside operation. Describe two methods by which this can be done. At what points can the transmission line be introduced?

m. Three parallel elements with half-wavelength spacing must be phased for broadside operation. Describe one method by which this is done. Do not use a method explained in answer to the previous question.

n. Explain how four parallel elements must be phased for broadside operation when full-wave spacing is used.

o. With what spacing will a broadside array be most efficient?

p. Explain two methods for phasing a pair of parallel elements for bidirectional end-fire operation. Choose one method using center feed.

q. At what spacing do end-fire elements provide the greatest gain? What problems arise at this spacing and how can they be overcome?

r. What is the input resistance of a pair of end-fire elements operated 180° apart with quarter-wavelength spacing?

s. What is the optimum length of the elements in the extended double-Zepp antenna?

t. Why is the lazy-H antenna array so named?

u. To what use can the closed-loop structure of the Sterba curtain be placed?

v. Why does the Bruce array illustrated in figure 171 produce a vertically polarized radio wave?

w. Describe the radiation pattern produced by the flat-top array.

x. What is a parasitic array?

y. Why is the physical length of a director shorter, and that of a reflector longer than the length of the driven element?

z. Name three factors that the gain and directivity of a parasitic array depend upon.

aa. Compare the characteristics of a parasitic array with those of a driven array.

ab. When a parasitic array is tuned for maximum power gain, is the front-to-back ratio also a maximum?

ac. Why is the radiation resistance of a parasitic array always lower than that of a driven array?

ad. What is a two-element beam? A three-element beam? A four-element beam?

ae. What are the advantages of using multiparasitic arrays?

af. Name the common methods for varying the length of parasitic elements.

ag. Why are parasitic arrays operated usually as *receiving* arrays when they are adjusted?

ah. What are the formulas used to determine the approximate physical lengths of a director, a reflector, and a driven element?

ai. Give the order in which the elements of a five-element beam are tuned.

CHAPTER 6

RADIO DIRECTION FINDING ANTENNAS

110. Directional Reception

Since the early days of radio, it has been known that a radio wave, when traveling between a transmitter and a receiver, almost always follows the shortest line along the surface of the earth, the Great Circle Path. For example, if a radio station located in New York City is radiating energy, that portion of the energy picked up by a receiver in Los Angeles, Calif., will travel diagonally across the United States. Thus, the problem of radio direction finding is reduced to that of determining the direction of arrival of a radio wave at the receiver. This determination is accomplished by using a directional receiving antenna, such as a loop or an Adcock antenna.

111. Loop Antenna

a. General. A loop antenna consists of one or more turns of conductor, either self-supporting or wound on an insulated frame. The most commonly used styles are diamond-shaped, square (fig. 184), or circular loops. These antennas all have a figure-8 response pattern. Thus, if a small transmitter is moved about a loop, unequal responses will be obtained at equal transmitter distances. Conversely, if a loop is rotated about its central vertical axis and the transmitter is held in one position, unequal responses will be obtained at different loop positions.

(1) The output voltage of these antennas is the result of phase differences between the voltages induced in opposite sides of the antenna. Consider that the single-turn loop of figure 185 is placed in the path of a vertically polarized wave. When the plane of the loop is in line with the direction of wave travel, as indicated, the wave front (fig. 11) reaches the sides of the loop at slightly different times (one side of loop is nearer the transmitter than the other side), producing a phase difference between the voltages induced in the two sides and giving rise to a resultant voltage across the antenna coupling coil. The resultant voltage is maximum when the plane of the loop is in line with the direction of wave travel. No voltage is induced in the horizontal sides of the loop because the vertically polarized wave travels parallel to them.

(2) If the loop then is rotated about its central vertical axis until the plane of the loop is perpendicular to the direction of wave travel, the wave front will reach the sides of the loop at the same time, the voltages induced in the two sides will be equal in magnitude and of the same phase, and, being directed in opposition through the coupling impedance, will cancel, thus resulting in a minimum output. The point of minimum response is called a *null.*

b. Pattern with Normal Polarization. When the incoming radio waves have vertical polarization, which is the normal condition under which a vertical loop would be used for direction finding, the loop antenna has a *figure-8* response pattern (fig. 186). In this illustration, the loop appears in the 90° to 270° position; any signal received from either of these directions will induce maximum signal into the receiver. As the loop is turned away from the direction from which the wave is arriving (90° to 270° position), the received signal decreases, reaching a minimum when the loop is in either the 0° or the 180° position. The line of direction of a transmitter can be determined by rotating the loop about its vertical axis until either a null or a maximum signal is produced. Then the transmitter direction is broadside to the loop at the null, or edgewise to the loop at the maximum, and the appropriate direction (azimuth) can be indicated by a pointer attached to the loop. It is customary to

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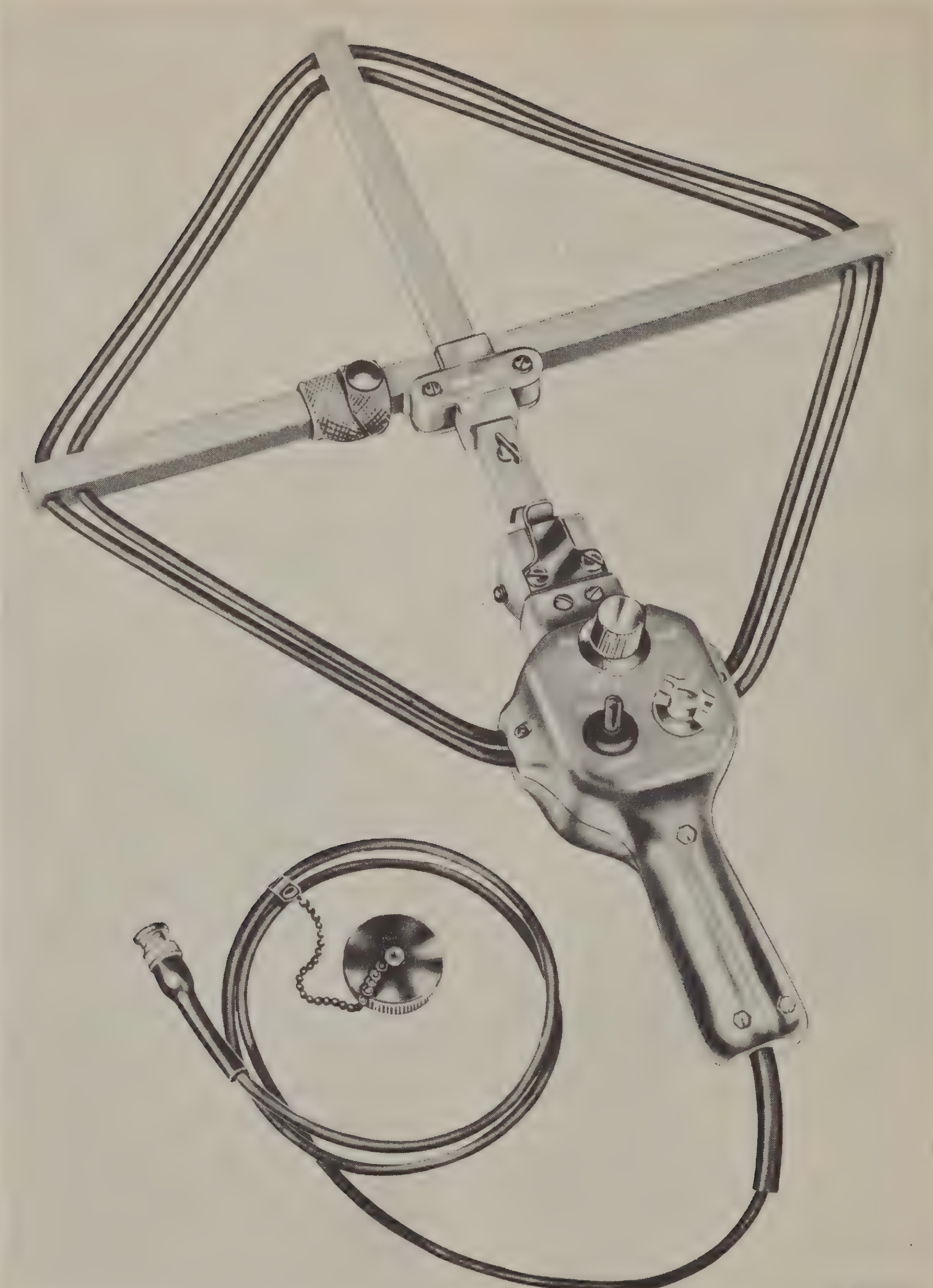

Figure 184. Loop antenna.

use the minimum rather than the maximum output of a loop when finding an azimuth. This permits a sharply defined indication and greater accuracy. The response pattern in figure 187 shows why this is so; maximum response of 100 microvolts is obtained with the loop edgewise to direction *A* (toward the transmitter). With the loop pointing toward *B*, a 10° rotation, there is only a 1.5-microvolt change in signal strength; this difference is not noticeable in the output. But with the loop broadside to a transmitter at *D*, a null position, a similar 10° rotation of the loop causes a 17.4-microvolt change in signal intensity.

c. Pattern with Abnormal Polarization. Since vertical polarization is considered normal for loop operation, any wave containing a horizontally

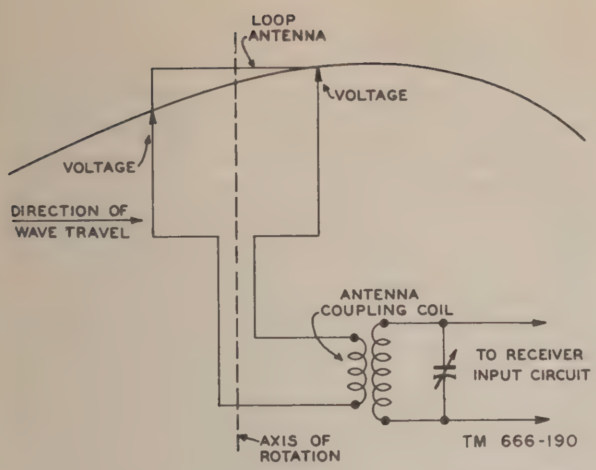

Figure 185. Simple loop antenna circuit, schematic diagram.

polarized component is considered as being abnormally polarized. A horizontally polarized wave has no effect on vertical conductors, but it will induce voltage in horizontal conductors such as those at the top and bottom of a loop. *The response pattern of a loop for horizontal polarization is a figure 8, with maximum broadside and null endwise to the horizontal conductors.* If the wave travels exactly horizontally, voltages induced in the top and bottom conductors will be equal and in phase; they will cancel each other in the loop output, just as do the voltages induced in the two sides by a (vertically polarized) wave arriving from the normal null direction (broadside). Thus, the horizontally polarized component of a wave produces little or no loop output when arriving at a low angle, but its effect becomes important when the wave is steeply downcoming (or upcoming). There will be an error of $\pm 90°$ in the azimuth determined by a simple loop direction finder if the polarization is assumed to be vertical when it

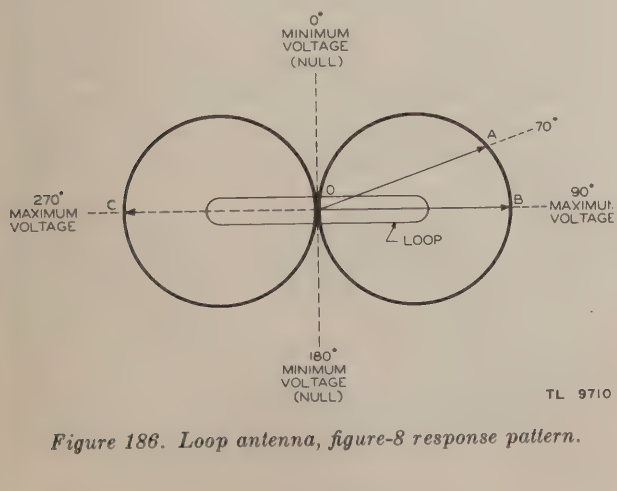

Figure 186. Loop antenna, figure-8 response pattern.

actually is horizontal. If the incoming wave has both vertically and horizontally polarized components, the figure-8 responses to the two components may combine to produce a figure 8 with sharp nulls, rotated in azimuth by some angle less than 90° from the normal position; this happens when the two components produce output voltages either in phase or 180° out of phase. When the two components produce voltages having other phase relations, the resulting response pattern may have its nulls filled in so that they become broad minima rather than zeros. In the special case where the two components produce equal output voltages 90° out of phase, the resulting response pattern becomes a perfect circle.

d. Ambiguity. Unless the general direction of the transmitter is known, a direction finder equipped with a simple loop antenna cannot determine whether a transmitter lies forward or to the rear of the direction finder. This 180°

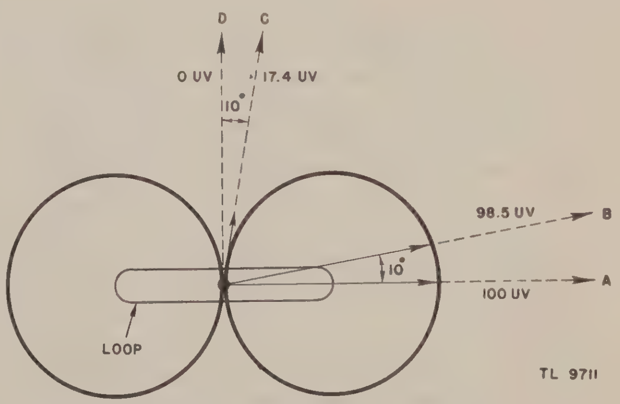

Figure 187. Change in loop position versus change in signal voltage.

ambiguity is caused by the two null positions of the loop, both of which indicate the same line of direction. There is no indication as to which of the two is the correct azimuth.

112. Loop and Sense Antennas

a. Purpose. The sense antenna is usually a vertical whip or monopole placed at the vertical axis of the loop. It is omnidirectional in azimuth. Both the circular response pattern of the sense antenna and the figure 8 pattern of the loop are symmetrical; but, when properly combined, the two antennas produce a lopsided or unidirectional pattern (cardioid pattern in fig. 188). The big end of this pattern lies to the right of one maxima, and to the left of the other maxima of the figure 8

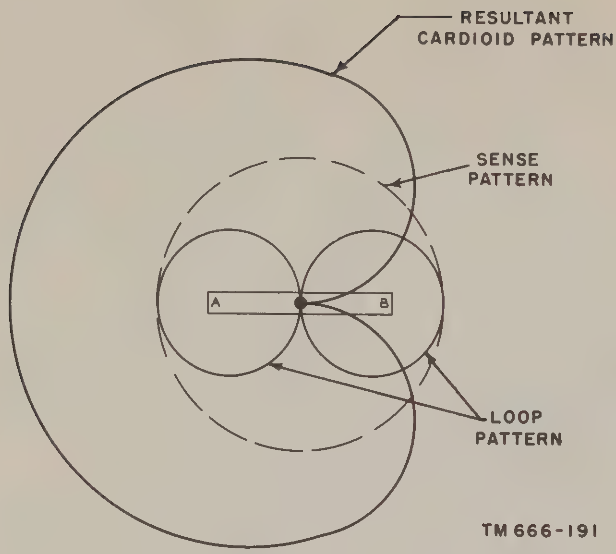

Figure 188. Cardioid response pattern obtained by combination of circular and figure 8 voltages.

pattern. By observing the relative positions of the unidirectional pattern, the two nulls can be distinguished, thus resolving the 180° ambiguity of the simple loop. One null is designated arbitrarily the front or direction null; the other is called the back or reciprocal null.

b. Application. After the loop has been rotated to a null, the direction it faces may be read from an azimuth scale or observed directly. Then the sense antenna is placed in operation, changing the response pattern from figure 8 to unidirectional. The null vanishes because of this change, and, upon turning the loop 90° to either side from the former null position, the response is found to be greater on one side than on the other. Which side is greater depends on whether the loop originally has its direct null facing toward or away from the transmitter. As a rule, if the response increases as the loop is turned clockwise, which increases the azimuth scale reading, or if the response *decreases* as the azimuth reading *decreases*, the direct null was toward the transmitter; if the response changes in the opposite direction, the reciprocal null was toward the transmitter. This relation is not always used. It can be reversed by transposing connections in the antenna circuit, to reverse the relative polarity of loop and sense antennas, or by a 180° shift in position of azimuth scale or pointer relative to the loop, and there are cases in which such a reversal has been made intentionally.

113. Cardioid Theory

When the voltages from loop and sense antennas are combined with the proper phase and amplitude the resulting pattern is a heart-shaped curve known to mathematicians as a cardioid. A typical case is illustrated in figures 189 and 190, and is explained, step by step, as follows:

a. A radio wave, traveling past the loop, as indicated in A of figure 189, strikes leg No. 1 a short time before it strikes leg No. 2.

b. The voltages induced in the two vertical legs are connected in series opposition, so that the net output of the loop depends on their difference.

c. As shown in *B* of figure 189, the voltage in leg No. 1 is starting to rise at time zero (t_0); the voltage induced in leg No. 2 starts to rise a short time later (t_2). However, so far as the output of the loop is concerned, the voltage induced in leg No. 2 is out of phase and begins to subtract from the voltage in leg No. 1 at this time (t_2).

d. Resultant voltage E_1 is developed across the output of the loop. This voltage is directly proportional to the time delay (phase shift) between the voltages induced in the legs of the loop. The greater the separation between t_0 and t_2 in *B* of figure 189, the greater the resultant loop voltage.

e. It is apparent in *B* of figure 189, that the resultant voltage leads the voltage induced in leg No. 1 approximately 90° and lags the voltage induced in leg No. 2 by the same amount.

f. Voltage E_3 induced in the vertical *sense* antenna is intermediate in phase between the voltage induced in the two legs of the loop, and therefore lags the resultant loop voltage, E_1, by 90°. To compensate for this phase difference (to have either an in-phase or an out-of-phase relation between resultant loop voltage E_1 and sense voltage E_3), it is necessary to advance or retard the phase of the loop voltage by 90° with a phase shifter. Retarded loop voltage E_2 is shown in *C* of figure 189. If the loop voltage had been advanced, it would be shifted 180° in phase from that shown in *C* of figure 189.

g. Notice that retarded loop voltage E_2 and sense voltage E_3, beginning at the same instant (t_1), are in phase. These two voltages add in the input transformer; the receiver voltage E_R is maximum (*E* of fig. 189).

h. If the antenna is rotated on its vertical axis through 180°, the electromagnetic wave strikes leg No. 2 before it strikes leg No. 1 (fig. 190).

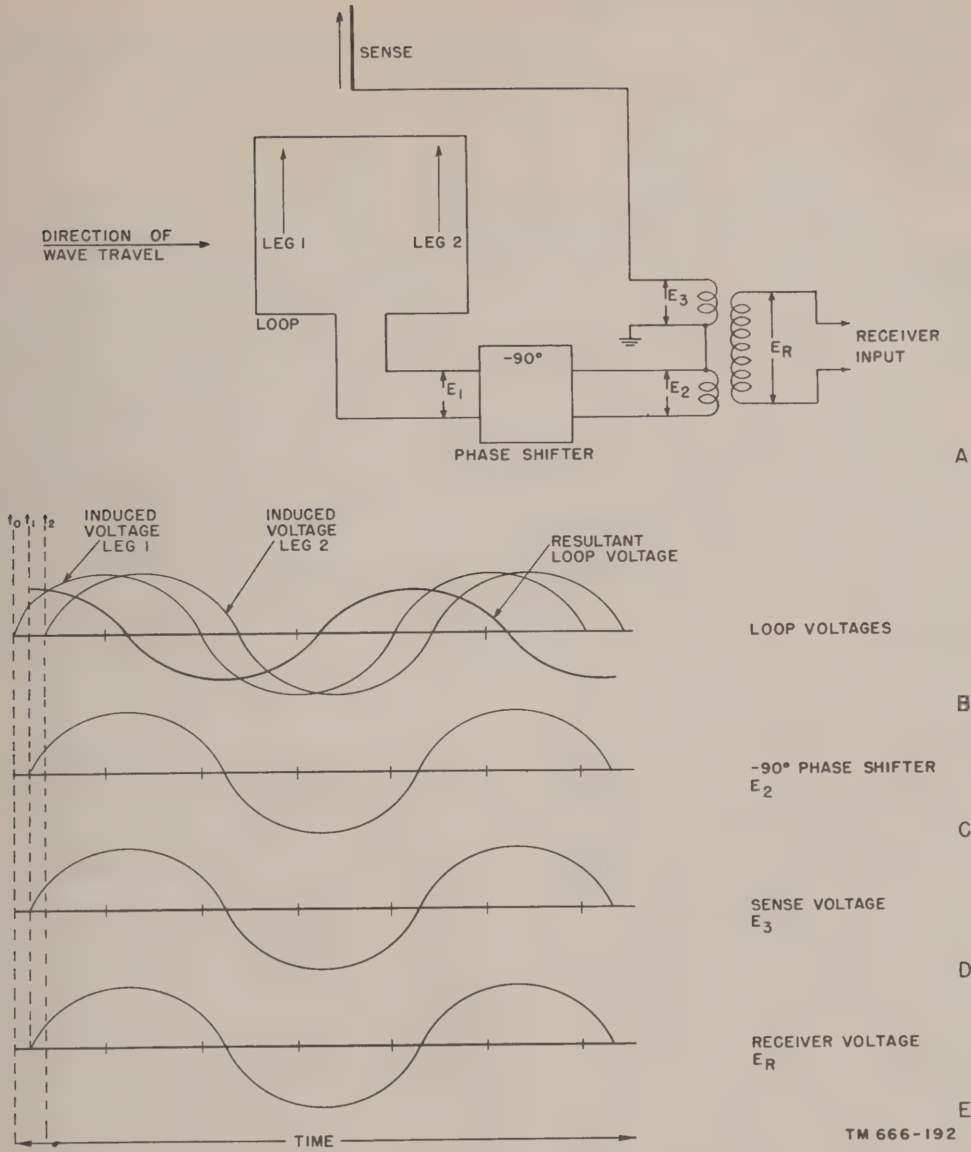

Figure 189 Loop and sense antenna system, relationship of voltages.

i. The voltages across both legs are induced in the same manner, producing a resultant again proportional to the separation between the legs. However, because of the loop rotation, the voltages of the two legs are interchanged, and resultant output voltage E_1 is shifted 180° in phase (*B* of fig. 190).

j. Retarded loop voltage E_R is, therefore, out of phase with the sense voltage, and minimum signal E is applied to the receiver (*C*, *D*, and *E* of fig. 190).

k. At intermediate points between the maximum and minimum positions of the loop, the following conditions exist. Assume that the transmitter azimuth is 0° as shown in figure 191.

(1) When the loop is rotated from 0° to 90°, loop voltage gradually decreases (distance between loop legs along the direction of wave travel becomes less). Sense voltage is constant and in phase with the loop voltage. Resultant receiver voltage is decreasing.

(2) When the loop is rotated from 90° to 180°, loop voltage gradually increases (distance between loop legs along the direction of wave travel becomes greater). Sense voltage is constant and 180° out of phase with the loop voltage. Resultant receiver voltage decreases because of the out-of-phase condition.

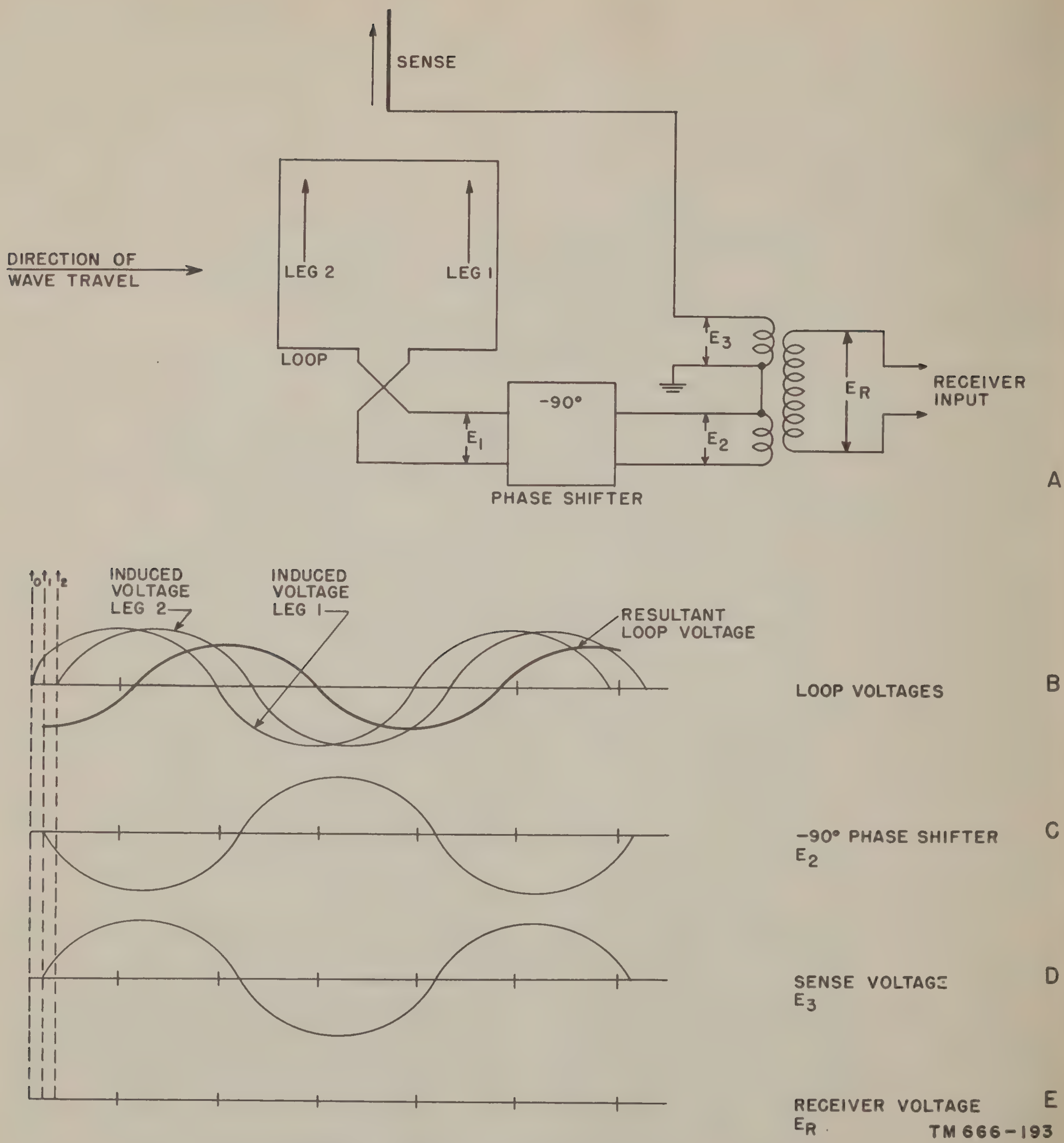

Figure 190. Relationship of voltages in loop and sense antenna system when loop has been rotated 180° from position shown in figure 189.

(3) When the loop is rotated from 180° to 270°, loop voltage gradually decreases. Sense voltage is constant and 180° out of phase with the loop voltage. Resultant receiver voltage increases.

(4) When the loop is rotated from 270° to 360°, loop voltage gradually increases. Sense voltage is constant and in phase with the loop voltage. Resultant receiver voltage increases.

l. Sense Voltage. In practice, sense circuits seldom are adjusted to the ideal condition just described, and the resulting unidirectional pattern is not a perfect cardioid. If the sense voltage is too

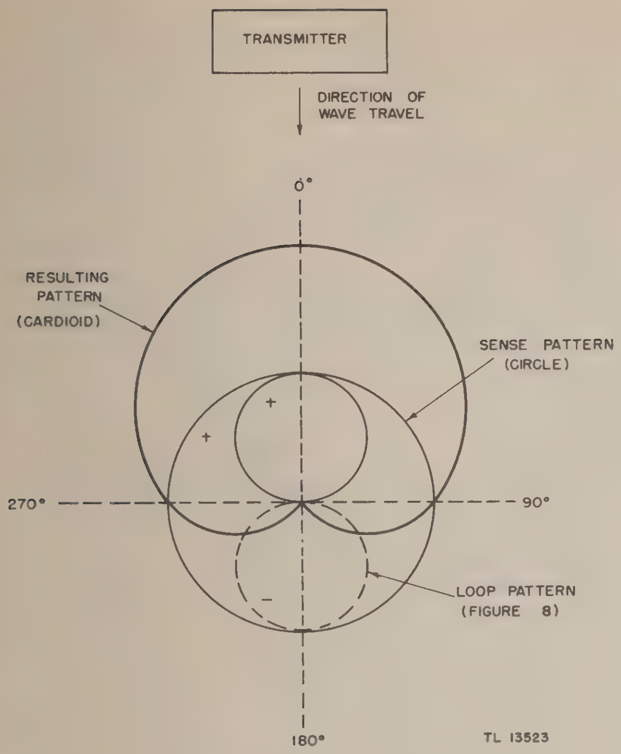

Figure 191. Cardioid response pattern.

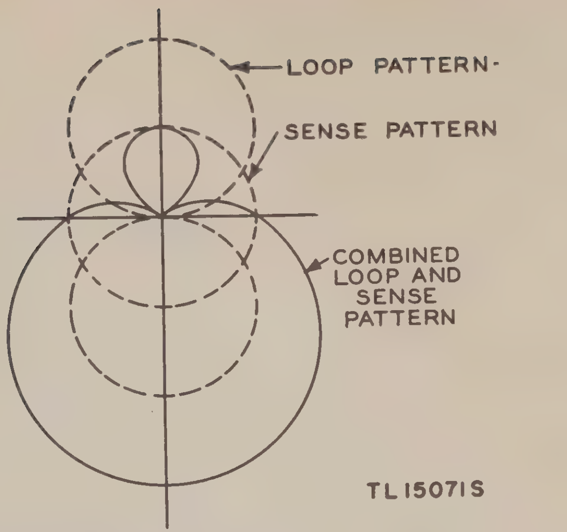

Figure 192. Response pattern, low sense voltage and correct phase relation.

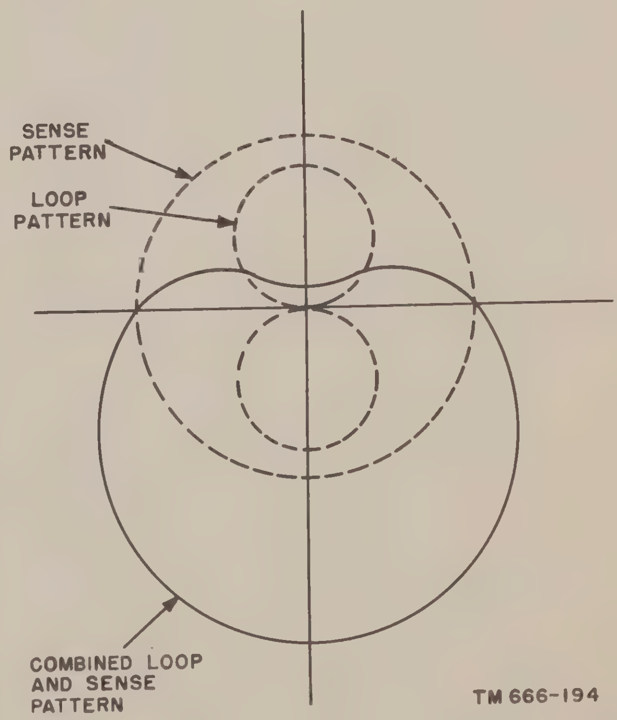

Figure 193. Response pattern, high sense voltage and correct phase relation.

small, the resultant pattern is a slightly lopsided figure 8. Increasing the sense voltage then makes the figure 8 more and more lopsided (fig. 192), until the sense voltage equals the maximum loop voltage; then one lobe disappears completely, making the pattern a perfect cardioid (fig. 191). Further increase of sense voltage increases both maximum and minimum of the resultant pattern (fig. 193), making it more and more like a circle. Either too little or too much sense voltage makes sense determination difficult, but any of the patterns just mentioned would be usable. The lopsidedness of the resultant pattern is readily distinguishable so long as the sense voltage is within ±50 percent of the maximum loop voltage. If the sense voltage is a little out of phase with the loop voltage, the resultant pattern becomes nearly circular, and the amplitude relation must be kept closer to the ideal for satisfactory operation. Figure 194 shows a case in which both amplitude and phase relation are far from the ideal. Here, the sense voltage has about half the amplitude shown in figure 192, and is 40° or 50° out of phase with the loop voltage. The lopsidedness of the resulting pattern could be detected by comparing its two maxima on a visual indicator, but the difference is too small to be detected by listening. If necessary (for example, if part of the sense antenna is lost), such a pattern can be used by observing which way the null shifts when the sense switch is operated; both nulls shift toward the small end of the lopsided figure 8 pattern.

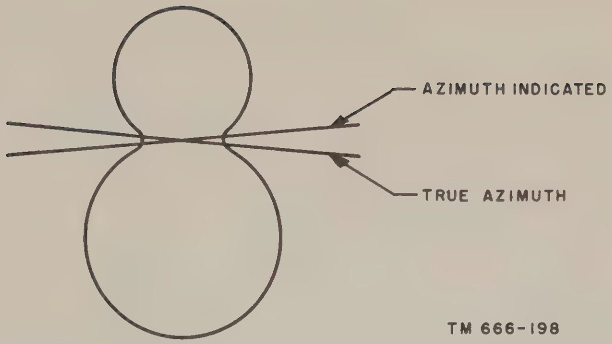

Figure 194. Response pattern, low sense voltage and incorrect phase relation.

114. Loop Construction

a. Balance. The most important single factor in the physical construction of a loop is its symmetry. When the loop is symmetrical physically, electrical balance is obtained, and if the balance is good enough, antenna effect (stray pick-up of sense voltage) is reduced to a minimum. Any conducting material near the loop, such as the top of the radio receiver case, should be placed symmetrically; otherwise the loop might be balanced at some positions but unbalanced at others. In the case of a square loop, it is preferable to place a corner rather than a side at the bottom; this arrangement keeps the body of the loop farther away from the ground so that any irregularities there (including metal items worn by the operator) are less likely to affect the loop balance.

b. Electrostatic Shield. Multiturn loops often are inclosed in an electrostatic shield. This is a metal case, or a film of metal on a case of some other material which surrounds the loop winding almost completely (fig. 195). At one point (the top) there is a gap in the metal, and opposite sides of the gap are insulated from each other to prevent the shield from forming a closed (short-circuited) loop. The shield is grounded near the loop terminals as far as possible from the insulated gap. As a vertical antenna, therefore, the shield is short-circuited. Consider the voltages induced by a passing radio wave as made up of two components, one corresponding to the desired loop voltage, the other to antenna effect. The former can produce very little current in the shield because of the insulated gap, but is fully effective in the loop which does have conductors crossing that gap. The latter component causes a flow of current over the shield to ground. Since the ground connection is a short circuit, this current produces in the shield counter electromotive force just equal to the original induced voltage, and it induces in each loop conductor a voltage which very nearly cancels the original antenna-effect voltage induced there by the radio wave. The reduction ratio is substantially the same as the reactance/resistance ratio which the shield would have if connected as a loop; since the Q is seldom less than 10, the residual antenna effect is seldom more than one-tenth the antenna effect with no shield. In addition to reducing antenna effect directly, the shield helps indirectly; unless very close to the gap in the shield, an external object cannot affect the capacitance from loop to ground and thus cannot change the capacitive balance of the loop. However, the shield affords no protection against inductive unbalance, such as might be caused by a scrap of metal placed too close to one side of the loop. The shield eliminates precipitation static of the type caused by electrically charged raindrops striking the antenna, and it provides mechanical protection for the loop.

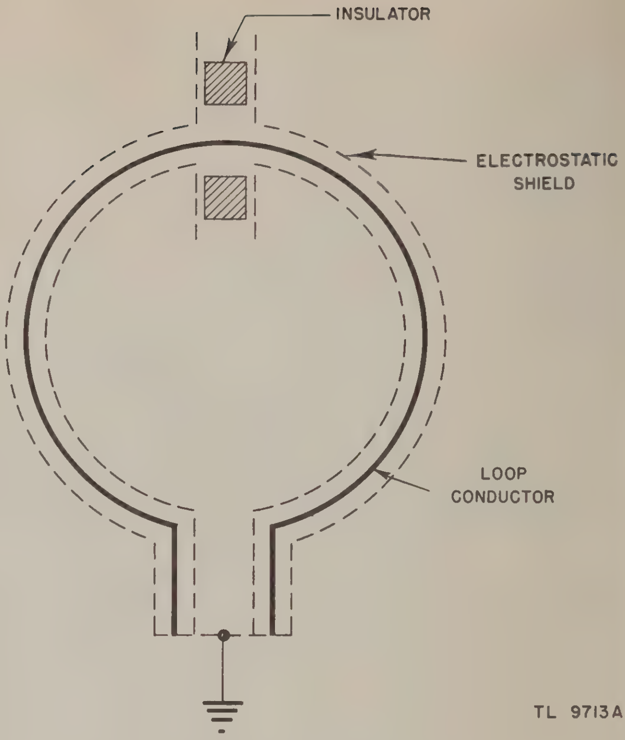

Figure 195. Shielded loop.

c. Loop Size. Except in some special vhf loops, which resemble groups of dipoles more than they do ordinary loops, the largest dimension of a loop antenna is usually a very small fraction of a wavelength (.1 wavelength at most). The voltage picked up by such a small loop is proportional to the total area inclosed by its turns; that is, to the

product of the number of turns by the average areas of each turn. For maximum pick-up, the turns should be as large as possible, subject to mechanical limitations, such as portability. The number of turns should be as large as possible, subject to electrical limitations. Most receivers will not operate efficiently from a loop which is self-resonant at any point within the operating frequency range; consequently, the number of turns must be small enough to keep the natural resonance higher than the highest operating frequency.

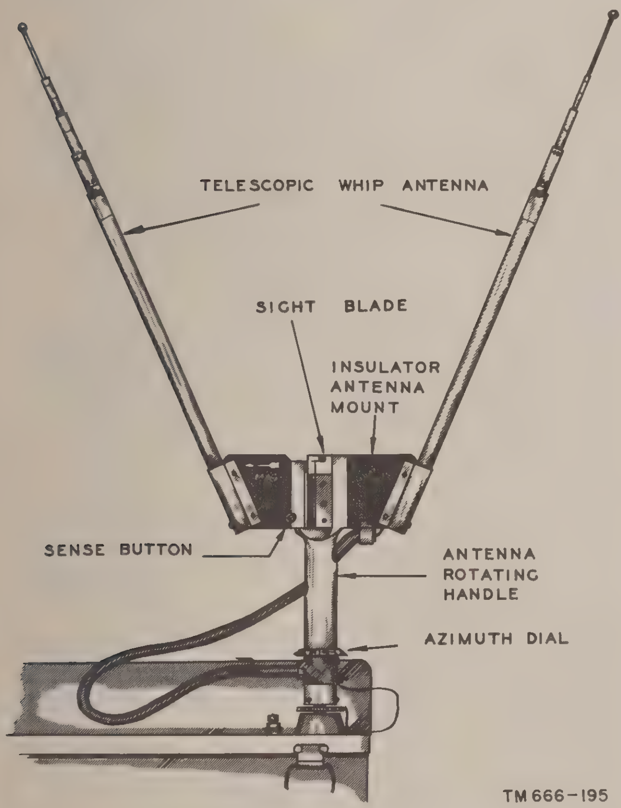

Figure 196. Simple Adcock antenna.

115. Adcock Antenna

a. General. An Adcock antenna (fig. 196) consists of two spaced vertical antennas connected in opposition. Theoretically, it responds only to the vertically polarized component of an incoming radio wave, and therefore is not subject to polarization error. In practice, some polarization error is caused by various imperfections, but usually much less than in a loop receiving the same signal. The Adcock antenna is preferable to a loop in radio D/F (direction finding) when medium- or high-frequency signals must be received at a point beyond ground-wave range.

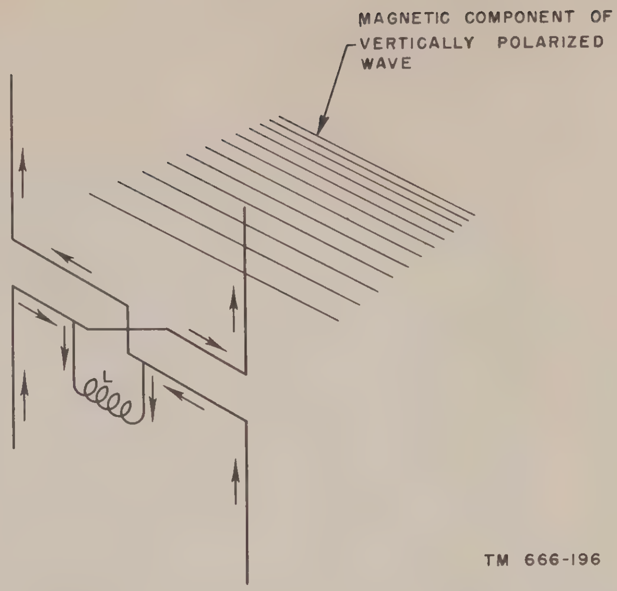

Figure 197. Adcock antenna, effects of vertically polarized wave.

b. Principle. The action of an Adcock antenna, as far as vertically polarized waves are concerned, is identical with that of the loop antenna. A resultant current in output coil L is proportional to the vector difference of the voltages induced in the vertical members, exactly as in the case of the loop. Horizontally polarized components of radio waves do not affect the antenna because of the absence of the upper and lower horizontal members, and because the crossed arrangement of the center members effectively cancels the voltages induced in them. The response pattern of an Adcock antenna is the same figure 8 pattern typical of the loop antenna. Minimum and maximum response points are present in the Adcock pattern in the same respective positions as in the loop pattern. Thus, the directional properties of the Adcock and loop antennas are the same with respect to vertically polarized waves. The effect of various types of wave polarization on the Adcock circuit are as follows:

(1) *Vertical polarization.* The horizontal magnetic lines of the vertically polarized wave cut the two vertical antenna elements. Induced currents, although they are induced in phase in the vertical elements, oppose each other in the antenna coupling coil, producing a resultant voltage which leads the radiation field by 90°. If the wave strikes both vertical elements simultaneously (antenna elements broadside to direction of wave

travel as shown in fig. 197), the resultant voltage is a minimum. At other angles of arrival, the resultant voltage is proportional to the separation between the two antenna elements along the direction of wave travel. Thus, the action of the Adcock antenna system is identical with the action of the loop system and can be used in conjunction with a sense antenna to obtain a unidirectional pattern.

(2) *Horizontal polarization.* As shown in figure 198, only the horizontal members (transmission lines) are in a position to respond to horizontally polarized waves. In a well designed radio direction finder, efficient use is made of shielding and balancing to prevent any voltages induced in the horizontal members from reaching the input tube of the receiver. The residue is small in comparison with the response of a loop under similar circumstances, but has the same directivity pattern.

(3) *Elliptical polarization.* Radio waves usually contain both vertical and horizontal components of polarization which, in combination, produce an elliptically polarized wave. Although the vertical and horizontal components can be viewed as acting independently, their effect on the antenna results from the combined action of both components. Because the response of an Adcock antenna is relatively small for the horizontally polarized component, its polarization error is likewise smaller than that of a loop antenna. This is true as long as the vertically polarized component does not entirely disappear; when the vertically polarized component predominates, the Adcock antenna has scarcely any polarization error.

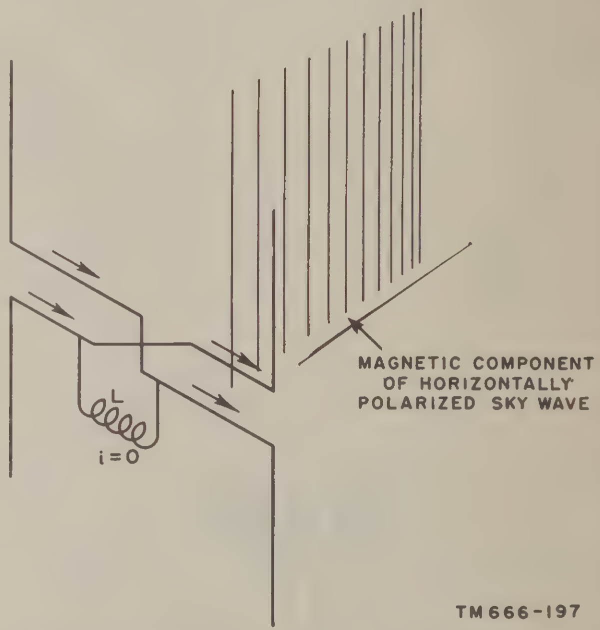

Figure 198. Adcock antenna, effects of horizontally polarized wave.

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